

---

## A Graph-Theoretic Network Security Game\*

---

Marios Mavronicolas<sup>†</sup>,  
Vicky G. Papadopoulou<sup>†‡</sup>,  
Anna Philippou<sup>†</sup> and Paul G. Spirakis<sup>‡</sup>

<sup>†</sup>Department of Computer Science, University of Cyprus, Nicosia  
CY-1678, Cyprus.

Fax: +357-22-892702 E-mail: {mavronic,viki,annap}@ucy.ac.cy

<sup>‡</sup>Corresponding author

<sup>‡</sup>Department of Computer Engineering and Informatics, University  
of Patras, Rion, Patras 26500, Greece.

Research Academic Computer Technology Institute, Rion, Patras  
26500, Greece.

Fax: +30-2610-960490 Email: spirakis@cti.gr

\*A preliminary version of this work appeared in the Proceedings  
of the *1st International Workshop on Internet and Network Eco-  
nomics*, pp. 969–978, Vol. 3827, Lecture Notes in Computer Sci-  
ence, Springer-Verlag, December 2005. This work has been par-  
tially supported by the IST Program of the European Union under  
contract numbers IST-2004-001907 (DELIS) and 15964 (AEOLUS).

**Abstract:** Consider a network vulnerable to viral infection, where  
the security software can guarantee safety only to a limited part of it.  
We model this practical network scenario as a non-cooperative multi-  
player game on a graph, with two kinds of players, a set of *attackers*  
and a *protector* player, representing the viruses and the system security  
software, respectively. Each attacker player chooses a node of the graph  
via a probability distribution to infect. The protector player chooses  
either an edge or a simple path of the network and cleans this part  
from attackers. Each attacker wishes to maximize the probability of  
escaping its cleaning by the protector. In contrast, the protector aims  
at maximizing the expected number of extinguished attackers. We call  
the two games obtained the *Path* and the *Edge* model, respectively.

We are interested in the associated *Nash equilibria*, where no net-  
work entity can unilaterally improve its local objective. We obtain the  
following results:

For certain families of graphs, mixed Nash equilibria can be computed  
in polynomially time. These families include, among others, regular  
graphs, graphs with perfect matchings and trees. The corresponding  
*Price of Anarchy* for any mixed Nash equilibria of the game is upper  
and lower bounded by a linear function of the number of vertices of  
the graph. (We define the Price of Anarchy to reflect the utility of the  
protector.) The problem of existence of a pure Nash equilibrium for the  
Path model is  $\mathcal{NP}$ -complete.

**Keywords:** Network Security Games, Nash equilibria, Graph Theory



**Biographical notes:** Marios Mavronicolas is a Professor of Computer Science at University of Cyprus. His research interests span the Theory of Algorithms and Complexity, with focus on Game Theory, Distributed and Parallel Computing, Networking and the Internet, where he has published widely in leading journals and conferences. He is on the Editorial Board of *Theoretical Computer Science*, *Journal of Interconnection Networks* and *Networks*. He previously held faculty positions at the University of Connecticut and the University of Crete. He holds a PhD in Computer Science from Harvard University.

Vicky Papadopoulou is a Post-Doctoral Researcher in Computer Science at University of Cyprus. Her research interests include Graph Theory, Algorithms, Computational Complexity, and Algorithmic Game Theory. She has published in prestigious journals and conference proceedings. She previously worked as Visiting Lecturer at the University of Cyprus and University of Patras. She holds a PhD in Computer Science from University of Patras.

Anna Philippou is an Assistant Professor of Computer Science at University of Cyprus. Her research interests include Concurrency Theory and its Applications, Specification and Verification of Concurrent Systems, Formal Methods, and Semantics of Programming Languages. She has published in several prestigious journals and conference proceedings. She previously worked as a Teaching Assistant at the University of Warwick and as a Postdoctoral Research Fellow at the University of Pennsylvania. She holds a PhD in Computer Science from University of Warwick.

Paul Spirakis is currently the Director of the RACTI and a Full Professor in the Patras University, Greece. His research interests Algorithms and Complexity and interaction of Complexity and Game Theory. He has extensively published in most of the important Computer Science journals and most of the significant refereed conferences. He was acknowledged between the top 50 scientists worldwide in Computer Science with respect to "The best Nurturers in Computer Science Research", published by B. Kumar and Y.N. Srikant, ACM Data Mining, 2005. He was elected unanimously as one of the two Vice Presidents of the Council of the EATCS. He holds a PhD in Computer Science from Harvard University.

---

## 1 Introduction

### 1.1 Motivation

This work considers a problem of *Network Security* related to the protection of a system from harmful procedures (e.g., viruses, worms). Consider an information network where the nodes of the network are insecure and vulnerable to infection from entities called *attackers*, such as viruses and Trojan horses. A *protector*, such as the system security software, is available to the system, but it can guarantee security only to a limited part of the network, such as a simple path or a single link of it. Each harmful entity targets a location (such as a node) of the network; the node is damaged unless it is cleaned by the system security software.



Apparently, the harmful entities and the system security software have conflicting objectives. The security software seeks to protect the network as much as possible, while the harmful entities wish to avoid being caught by the software so that they be able to damage the network. Thus, the system security software seeks to maximize the expected number of viruses it catches, while each harmful entity seeks to maximize the probability it escapes from the security software.

Naturally, we model this scenario as a *non-cooperative strategic game* played on a graph with two kinds of players: the *vertex players* representing the harmful entities, and the *edge* or the *path player* representing the system security software considered in each of the two cases, choosing a single edge or a simple path, respectively. The corresponding games are called the **Edge** and the **Path** model, respectively. In each model, each player seeks to maximize her *Individual Profit*. We are interested in the *Nash equilibria* (12; 13) associated with these games, where no player can unilaterally improve its Individual Profit by switching to a more advantageous probability distribution.

We measure the system performance utilizing *Social Cost* (5), defined as the number of attackers caught by the protector.

## 1.2 Contribution

Our results are summarized as follows:

### 1.2.1 The Edge Model

*r-Factorizable, Regular and Perfect Matching Graphs.* Although (8) provides a graph-theoretic characterization of mixed Nash Equilibria for the Edge model, the characterization only implies an exponential time algorithm for the case of general graphs. Here, we utilize the characterization to provide polynomial time algorithms to compute mixed Nash equilibria for *specific* graphs. In particular, we combine the characterization with a suitable exploration of some graph-theoretic properties of each graph family considered to obtain polynomial time *structured* mixed Nash equilibria.

We consider *r-factorizable* graphs, which contain a spanning *r*-regular subgraph, for some positive integer *r*. We show that an *r*-factorizable graph *G* admits a mixed Nash equilibrium that can be computed in time  $O(T(G))$ , where  $O(T(G))$  is the time needed for the computation of an *r*-factor of *G* (Theorem 3.1). So, if  $T(G)$  is a polynomial function, a Nash equilibrium can be computed in polynomial time (Corollary 3.2). Also, this implies that *regular* graphs admit polynomially computable Nash equilibria (Corollary 3.3). Furthermore, since a graph with a Perfect Matching (called *Perfect Matching graph*) is an 1-factorizable graph and a Perfect Matching can be computed in polynomial time (3), the same result implies that Perfect Matching graphs admit polynomial time Nash equilibria (Corollary 3.4).

*Trees.* We present a *linear* time algorithm for computing a mixed Nash equilibrium for a tree (Theorem 3.5). This improves an algorithm to compute such an equilibrium that runs in time  $O\left(\sqrt{|V||E|} \cdot \log_{|V|} \frac{|V|^2}{|E|}\right)$  from (10).

*Price of Anarchy.* We present upper and lower bounds on the Social Cost of any

mixed Nash equilibrium in the Edge model (Theorem 3.10). Using these bounds, we show that the corresponding Price of Anarchy is upper and lower bounded by a linear function of the number of vertices of the graph (Theorem 3.12).

### 1.2.2 The Path Model

We prove that the existence problem of pure Nash equilibria in the Path model is  $\mathcal{NP}$ -complete (Theorem 4.4). This is in contrast to the Edge model, where no instance has a pure Nash equilibrium (8, Theorem 1).

### 1.3 Related Work and Significance

This work is a step further in the development of *Algorithmic Game Theory*. It is also one of the very few works modeling network security problems using strategic games. Such a research line is that of *Interdependent Security* games (1). However, *none* of these works, with an exception of (1), studied the associated Nash equilibria. In (1), the authors studied a particular Virus Inoculation game and established connections with variants of the Graph Partition problem.

The Edge model was introduced and studied in (8), where a non-existence result for pure Nash equilibria (for any instance) and a polynomial time algorithm to compute mixed Nash equilibria for bipartite graphs were provided.

(10) provided a polynomial time characterization of graphs admitting a class of *structured* Nash equilibrium the so called *Matching Nash equilibria*. The characterization implies that trees admit such equilibria. They also presented an algorithm to compute such them (if such one exists) for a graph that runs in time  $O\left(\sqrt{|V||E|} \cdot \log_{|V|} \frac{|V|^2}{|E|}\right)$ . Here, we present a more efficient, *linear* time algorithm for computing a *structured* Nash equilibrium for a tree. More recently, (9) showed that a more general class of graphs admits polynomial time computable Nash equilibria; the graphs with Fractional Perfect Matchings.

Recently, generalizations of the Edge model have been introduced and investigated:

- In (4), the protector is able to scan and protect a set of  $k$  links of the network. That work presented a polynomial time algorithm for computing pure and mixed Nash equilibria and a polynomial-time transformation of a special class of structured Nash equilibria between the Edge model and the generalized model.
- In the generalization considered in (7), there is a number of *interdependent* protectors with a *reward-sharing* scheme. The results in (7) provide interesting trade-offs between the number of the protectors and the amount of protection.

## 2 Framework

Throughout, we consider an undirected graph  $G = G(V, E)$  with no isolated vertices;  $G$  is *non-trivial* whenever it has more than one edges, otherwise it is

trivial.

### 2.1 Graph Theory

For a vertex set  $U \subseteq V$ , denote  $G(U)$  the subgraph of  $G$  induced by  $U$ ; denote  $\text{Edges}_G(U) = \{(u, v) \in E \mid u, v \in U\}$ . For an edge set  $E' \subseteq E$ , denote  $\text{Vertices}_G(E') = \{v \in V \mid (v, u) \in E'\}$ . For a vertex set  $U \subseteq V$ , denote  $\text{Neigh}_G(U) = \{u \notin U \mid (u, v) \in E \text{ for some vertex } v \in U\}$ . For an edge set  $F \subseteq E$ , denote  $G(F)$  the subgraph of  $G$  induced by  $F$ . For a vertex set  $U \subseteq V$ , the graph  $G \setminus U$  is obtained by  $G$  by removing the vertices of set  $U$  and their incident edges. For a vertex  $v \in V$ , denote  $\Delta_G(v)$  the degree of vertex  $v$  and  $\Delta(G) = \max_{v \in V} \Delta_G(v)$ .

- An **Independent Set** is a vertex set  $IS \subseteq V$  such that for all pairs of vertices  $u, v \in IS$ ,  $(u, v) \notin E$ .
- A **Vertex Cover** is a vertex set  $VC \subseteq V$  such that for each edge  $(u, v) \in E$  either  $u \in VC$  or  $v \in VC$ .
- An **Edge Cover** is an edge set  $EC \subseteq E$  such that for every vertex  $v \in V$ , there is an edge  $(v, u) \in EC$ .
- A **Matching** is a set  $M \subseteq E$  of non-incident edges. A *Maximum Matching* is one that has maximum size;  $\alpha'(G)$  denotes the size of a Maximum Matching and it is called the **Matching Number**. The currently fastest algorithm to compute a Maximum Matching of  $G$  appears in (3) and has running time  $O\left(\sqrt{|V||E|} \cdot \log_{|V|} \frac{|V|^2}{|E|}\right)$ . It is known that a Minimum Edge Cover can be computed in polynomial time via computing a Maximum Matching. (See, e.g., (15, page 115).) A **Perfect Matching** is a Matching that is also an Edge Cover. A graph that admits a Perfect matching is called **Perfect Matching** graph.
- A (simple) *path* is a sequence  $v_1, v_2, \dots, v_k$  of distinct vertices from  $V$  such that  $v_i, v_{i+1} \in E$  for  $1 \leq i < k$ ; say that the path has *size*  $k$ . A **Hamiltonian path** is a path that includes all vertices from  $V$ . A graph containing a Hamiltonian path is called *Hamiltonian*. It is well known that answering the question whether a given graph is Hamiltonian is an  $\mathcal{NP}$ -complete (2, problem GT39). Denote  $\text{Paths}(G)$  the set of all possible paths in  $G$ .
- For a **rooted** tree graph  $T = (V, E)$  denote  $root \in V$ , the root of the tree and  $leaves(T)$  the leaves of the tree  $T$ . For any  $v \in V$ , denote  $parent_T(v)$  the parent of  $v$  in the tree and  $children_T(v)$  its children in the tree  $T$ . For any  $A \subseteq V$ , let  $parents_T(A) := \{u \in V \mid u = parent_T(v), v \in A\}$ .
- For an integer  $r$ , graph  $G$  is  **$r$ -regular** if  $\Delta_G(v) = r, \forall v \in V$ . A  **$r$ -factor** of a graph  $G$ , is a spanning subgraph of  $G$  such that  $\Delta_{G_r}(v) = r$  for any  $v \in V$ . We denote it as  $G_r = (V, E')$ , where  $E' \subseteq E$ . A graph containing an  $r$ -factor is called  **$r$ -factorizable**. For an 1-factor of  $G$ , its edge set is a Perfect Matching of  $G$ . A 2-factor of a graph, also called *cycle cover*, (if there exists) can



be computed in polynomial time, via Tutte's reduction (14) to the classical Perfect Matching problem (see (6, Sect. 10.1)). Thus, the currently most efficient algorithm for its computation needs time  $O\left(\sqrt{|V|}|E| \cdot \log_{|V|} \frac{|V|^2}{|E|}\right)$  (3).

A graph  $G$  is called **polynomially computable  $r$ -factorizable** if it contains an  $r$ -factor subgraph that can be computed in polynomial time. It can be easily seen that there exist exponential many such graph instances.

## 2.2 The Edge Model

Associated with  $G$  is a **strategic game**  $\Pi_E(G) = \langle \mathcal{N}, \{S_i\}_{i \in \mathcal{N}}, \{IP\}_{i \in \mathcal{N}} \rangle$  on  $G$ :

- The set of **players** is  $\mathcal{N} = \mathcal{N}_{vp} \cup \mathcal{N}_{ep}$ , where  $\mathcal{N}_{vp}$  contains  $\nu$  **vertex players**  $vp_i$ ,  $1 \leq i \leq \nu$  and  $\mathcal{N}_{ep}$  contains a single **edge player**  $ep$ .
- The **strategy set**  $S_i$  of vertex player  $vp_i$  is  $V$ ; the **strategy set**  $S_{ep}$  of the edge player  $ep$  is  $E$ . So, the **strategy space**  $\mathcal{S}$  of the game is  $\mathcal{S} = \left(\prod_{i \in \mathcal{N}_{vp}} S_i\right) \times S_{ep} = V^\nu \times E$ .
- Fix any **profile**  $\mathbf{s} = \langle s_1, \dots, s_\nu, s_{ep} \rangle \in \mathcal{S}$ , also called a **pure profile**:
  - The **Individual Profit** of vertex player  $vp_i$  is a function  $IP_i(\mathbf{s}) : \mathcal{S} \rightarrow \{0, 1\}$  such that  $IP_i(\mathbf{s}) = \begin{cases} 0, & s_i \in s_{ep} \\ 1, & s_i \notin s_{ep} \end{cases}$ ; so, the vertex player  $vp_i$  receives 1 if it is not caught by the edge player, and 0 otherwise.
  - The **Individual Profit** of the edge player  $ep$  is a function  $IP_{ep}(\mathbf{s}) : \mathcal{S} \rightarrow \mathbb{N}$  such that  $IP_{ep}(\mathbf{s}) = |\{i : s_i \in s_{ep}\}|$ ; so, the edge player  $ep$  receives the number of vertex players it catches.

### 2.2.1 Pure Strategies and Pure Nash Equilibria

The profile  $\mathbf{s}$  is a **pure Nash equilibrium** (12; 13) if for each player  $i \in \mathcal{N}$ , it maximizes  $IP_i(\mathbf{s})$  over all profiles  $\mathbf{t}$  that differ from  $\mathbf{s}$  only with respect to the strategy of player  $i$ . Intuitively, in a pure Nash equilibrium, vertex player (resp., the edge player) can (resp., cannot) improve its Individual Profit by switching to a different vertex (resp., edge). In other words, a pure Nash equilibrium is a *local maximizer* for the Individual Profit of each player. Say that  $G$  *admits* a pure Nash equilibrium if there is a pure Nash equilibrium for the strategic game  $\Pi_E(G)$ .

### 2.2.2 Mixed Strategies and Profiles

A **mixed strategy** for player  $i \in \mathcal{N}$  is a probability distribution over  $S_i$ ; thus, a mixed strategy for a vertex player (resp., edge player) is a probability distribution over vertices (resp., edges). A **mixed profile**  $\mathbf{s} = \langle s_1, \dots, s_\nu, s_{ep} \rangle$  is a collection

of mixed strategies;  $s_i(v)$  is the probability that vertex player  $vp_i$  chooses vertex  $v$  and  $s_{ep}(e)$  is the probability that the edge player  $ep$  chooses edge  $e$ .

The **support** of player  $i \in \mathcal{N}$  in the profile  $\mathbf{s}$ , denoted  $\text{Support}_i(\mathbf{s})$ , is the set of pure strategies in its strategy set to which  $i$  assigns a strictly positive probability in  $\mathbf{s}$ . Denote  $\text{Support}_{vp}(\mathbf{s}) = \bigcup_{i \in \mathcal{N}_{vp}} \text{Support}_i(\mathbf{s})$ . Set  $\text{Edges}_v(\mathbf{s}) = \{(u, v) \in E : (u, v) \in \text{Support}_{ep}(\mathbf{s})\}$ . So,  $\text{Edges}_v(\mathbf{s})$  contains all edges incident to  $v$  that are included in the support of the edge player. For a vertex set  $U \subseteq V$ , set  $\text{Edges}_U(\mathbf{s}) = \{e = (u, v) \in \text{Support}_{ep}(\mathbf{s}) : u \in U\}$ . So,  $\text{Edges}_U(\mathbf{s})$  contains all edges incident to a vertex in  $U$  that are included in the support of the edge player.

For a vertex  $v \in V$ , the probability the edge player  $ep$  chooses an edge that contains the vertex  $v$  is denoted  $P_{\mathbf{s}}(\text{Hit}(v))$ . Clearly,  $P_{\mathbf{s}}(\text{Hit}(v)) = \sum_{e \in \text{Edges}_v(\mathbf{s})} s_{ep}(e)$ . For a vertex  $v \in V$ , denote as  $\text{VP}_v(\mathbf{s})$  the expected number of vertex players choosing vertex  $v$  according to  $\mathbf{s}$ ; so,  $\text{VP}_v(\mathbf{s}) = \sum_{i \in \mathcal{N}_{vp}} s_i(v)$ . For each edge  $e = (u, v) \in E$ ,  $\text{VP}_e(\mathbf{s})$  is the expected number of vertex players choosing either the vertex  $u$  or the vertex  $v$ .

### 2.2.3 Expected Individual Profit and Conditional Expected Individual Profits

A mixed profile  $\mathbf{s}$  induces an **Expected Individual Profit**  $\text{IP}_i(\mathbf{s})$  for each player  $i \in \mathcal{N}$ , which is the expectation according to  $\mathbf{s}$  of the Individual Profit of player  $i$ .

Induced by the mixed profile  $\mathbf{s}$  is also the **Conditional Expected Individual Profit**  $\text{IP}_i(\mathbf{s}_{-i}, v)$  of vertex player  $vp_i \in \mathcal{N}_{vp}$  on vertex  $v \in V$ , which is the conditional expectation according to  $\mathbf{s}$  of the Individual Profit of player  $vp_i$  had it chosen vertex  $v$ . So,

$$\begin{aligned} \text{IP}_i(\mathbf{s}_{-i}, v) &= 1 - P_{\mathbf{s}}(\text{Hit}(v)) \\ &= 1 - \sum_{e \in \text{Edges}_v(\mathbf{s})} s_{ep}(e) \end{aligned}$$

Clearly, for the vertex player  $vp_i \in \mathcal{N}_{vp}$ ,

$$\begin{aligned} \text{IP}_i(\mathbf{s}) &= \sum_{v \in V} s_i(v) \cdot \text{IP}_i(\mathbf{s}_{-i}, v) \\ &= \sum_{v \in V} s_i(v) \cdot \left( 1 - \sum_{e \in \text{Edges}_v(\mathbf{s})} s_{ep}(e) \right). \end{aligned}$$

Finally, induced by the mixed profile  $\mathbf{s}$  is the **Conditional Expected Individual Profit**  $\text{IP}_{ep}(\mathbf{s}_{-ep}, e)$  of the edge player  $ep$  on edge  $e = (u, v) \in E$ , which is the conditional expectation according to  $\mathbf{s}$  of the Individual Profit of player  $ep$  had it chosen edge  $e$ . So,

$$\begin{aligned} \text{IP}_{ep}(\mathbf{s}_{-ep}, e) &= \text{VP}_e(\mathbf{s}) \\ &= \sum_{i \in \mathcal{N}_{vp}} (s_i(u) + s_i(v)). \end{aligned}$$



Clearly, for the edge player  $ep$ ,

$$\begin{aligned} \text{IP}_{ep}(\mathbf{s}) &= \sum_{e \in E} s_{ep}(e) \cdot \text{IP}_{ep}(\mathbf{s}_{-ep}, e) \\ &= \sum_{e=(u,v) \in E} s_{ep}(e) \cdot \left( \sum_{i \in \mathcal{N}_{vp}} (s_i(u) + s_i(v)) \right). \end{aligned}$$

#### 2.2.4 Mixed Nash Equilibria

The mixed profile  $\mathbf{s}$  is a ***mixed Nash equilibrium*** (12; 13) if for each player  $i \in \mathcal{N}$ , it maximizes  $\text{IP}_i(\mathbf{s})$  over all mixed profiles  $\mathbf{t}$  that differ from  $\mathbf{s}$  only with respect to the mixed strategy of player  $i$ . In other words, a Nash equilibrium  $\mathbf{s}$  is a *local maximizer* for the Expected Individual Profit of each player. By Nash's celebrated result (12; 13), there is at least one mixed Nash equilibrium for the strategic game  $\Pi_E(G)$ ; so, every graph  $G$  admits a mixed Nash equilibrium.

The particular definition of Expected Individual Profits implies in a Nash equilibrium, for each player  $i \in \mathcal{N}$  and strategy  $x \in S_i$  such that  $s_i(x) > 0$ , all Conditional Expected Individual Profits  $\text{IP}_i(\mathbf{s}_{-i}, x)$  are the same and no less than any Conditional Expected Individual Profit  $\text{IP}_i(\mathbf{s}_{-i}, x')$  with  $s_i(x') = 0$ , where  $x' \in S_i$ . It follows that:

- For each vertex player  $vp_i$ , for any vertex  $v \in \text{Support}_i(\mathbf{s})$ ,

$$\text{IP}_i(\mathbf{s}) = 1 - \sum_{e \in \text{Edges}_v(\mathbf{s})} s_{ep}(e).$$

- For the edge player  $ep$ , for any edge  $(u, v) \in \text{Support}_{ep}(\mathbf{s})$ ,

$$\text{IP}_{ep}(\mathbf{s}) = \sum_{i \in \mathcal{N}_{vp}} (s_i(u) + s_i(v)).$$

Note that for each vertex player  $vp_i$ , there is some vertex  $v$  such that  $s_i(v) > 0$ ; since a Nash equilibrium  $\mathbf{s}$  maximizes the Individual Profit of the edge player  $ep$ , it follows that  $\text{IP}_{ep}(\mathbf{s}) > 0$  for a Nash equilibrium  $\mathbf{s}$ . A profile  $\mathbf{s}$  is ***uniform*** if each player uses a uniform probability distribution on her support.

#### 2.2.5 Background

In (8, Theorem 1) it was proved that if  $G$  contains more than one edges, then  $\Pi_E(G)$  has no pure Nash Equilibrium. We use a characterization of Nash equilibrium proved in the same work:

**Theorem 2.1 ((8))** *A profile  $\mathbf{s}$  is a Nash equilibrium if and only if (1) for each vertex  $v \in \text{Support}_{vp}(\mathbf{s})$ ,  $P_{\mathbf{s}}(\text{Hit}(v)) = \min_{v' \in V} P_{\mathbf{s}}(\text{Hit}(v'))$ , and (2) for each edge  $e \in \text{Support}_{ep}(\mathbf{s})$ ,  $\text{VP}_e(\mathbf{s}) = \max_{e' \in E} \text{VP}_{e'}(\mathbf{s})$ .*

We also use the notion of ***Covering profiles***, introduced in (8). A covering profile is a profile  $\mathbf{s}$  such that (1)  $\text{Support}_{ep}(\mathbf{s})$  is an Edge Cover of  $G$  and (2)  $\text{Support}_{vp}(\mathbf{s})$  is a Vertex Cover of the graph  $G(\text{Support}_{ep}(\mathbf{s}))$ . It turns out that Covering profiles are interesting:

**Proposition 2.2 ((8))** *A Nash Equilibrium is a Covering profile.*

An **Independent Covering profile** (8)  $\mathbf{s}$  is a uniform Covering profile in which  $s_i = s_j$ , for any two vertex players  $i, j \in \mathcal{N}_{vp}$  such that (1)  $\text{Support}_{vp}(\mathbf{s})$  is an Independent Set and (2) each vertex in  $\text{Support}_{vp}(\mathbf{s})$  is incident to exactly one edge in  $\text{Support}_{ep}(\mathbf{s})$ . Our analysis uses the following previous result:

**Theorem 2.3 ((10))** *An Independent Covering profile is a Nash equilibrium.*

### 2.3 The Path Model

We now introduce a generalization of the Edge model  $\Pi_E(G)$ . The generalization consists of allowing the prodector (edge player in the Edge model) to select a path of  $G$ , instead of a single edge. We call this generalization as the **Path model** and denote it as  $\Pi_P(G) = \langle \mathcal{N}, \{S_i\}_{i \in \mathcal{N}}, \{IP\}_{i \in \mathcal{N}} \rangle$ . The only difference with  $\Pi_E(G)$  is that:

- (i)  $\mathcal{N} = \mathcal{N}_{vp} \cup \mathcal{N}_{pp}$ , where  $\mathcal{N}_{vp}$  is defined as before but  $\mathcal{N}_{pp}$  contains a single *path* player  $pp$  (which replaces the edge player)
- (ii)  $s_{pp} = \text{Paths}(G)$ .

Thus, the **strategy set**  $\mathcal{S}$  of  $\Pi_P(G)$  is  $\mathcal{S} = \left( \prod_{i \in \mathcal{N}_{vp}} S_i \right) \times S_{pp} = V^\nu \times |\text{Paths}(G)|$ .

Note that the strategy set of  $\Pi_P(G)$  is *exponential*, as the number of distinct paths of the graph.

#### 2.3.1 Nash Equilibria

In the same way as for  $\Pi_E(G)$ , we define a **pure Nash equilibrium** for  $\Pi_P(G)$ . Similarly, we define a **mixed strategy**  $s_i$  for player  $i \in \mathcal{N}$  and a **mixed profile**  $\mathbf{s}$  for  $\Pi_P(G)$ . In a mixed profile  $\mathbf{s}$ , we define the support  $\text{Support}_i(\mathbf{s})$  for player  $i \in \mathcal{N}$ . Also, we define  $\text{Paths}_v(\mathbf{s}) = \{p \in \text{Paths}(G) : p \in \text{Support}_{pp}(\mathbf{s}) \text{ and } v \in \text{Vertices}_G(p)\}$ . For a vertex  $v \in V$ , the probability the path player  $pp$  chooses a path that contains the vertex  $v$  is denoted  $P_{\mathbf{s}}(\text{Hit}(v))$ . Clearly,  $P_{\mathbf{s}}(\text{Hit}(v)) = \sum_{p \in \text{Paths}_v(\mathbf{s})} s_{pp}(p)$ . For a vertex  $v \in V$ , we define  $\text{VP}_v(\mathbf{s})$  as in  $\Pi_E(G)$ . So, for a path  $p \in \text{Paths}(G)$ , we denote  $\text{VP}_p(\mathbf{s}) = \sum_{v \in \text{Vertices}_G(p)} \sum_{i \in \mathcal{N}_{vp}} s_i(v)$ .

Similarly to  $\Pi_E(G)$ , we define the **Expected Individual Profit**  $\text{IP}_i(\mathbf{s})$ , and the **Conditional Expected Individual Profit**  $\text{IP}_i((\mathbf{s}_{-i}, x))$ , of player  $i$ , for a strategy  $x \in S_i$ . So, for any vertex player  $vp_i \in \mathcal{N}_{vp}$ , for any vertex  $v \in V$ ,  $\text{IP}_i((\mathbf{s}_{-i}, v)) = 1 - P_{\mathbf{s}}(\text{Hit}(v))$ . For the path player, for any path  $p \in \text{Paths}(G)$ ,  $\text{IP}_{pp}((\mathbf{s}_{-pp}, p)) = \text{VP}_p(\mathbf{s})$ .

### 2.4 Social Cost and Price of Anarchy

We utilize the notion of **social cost** (5) for evaluating the system performance.



**Definition 2.1** For model  $M$ ,  $M = \{P, E\}$ , we define the **social cost** of configuration  $\mathbf{s}$  on instance  $\Pi_M(G)$ ,  $SC(\Pi_M, \mathbf{s})$ , to be the (expected) sum of vertex players of  $\Pi_M$  arrested in  $\mathbf{s}$ . That is,  $SC(\Pi_M, \mathbf{s}) = IP_p(\mathbf{s})$  ( $p = \{pp, ep\}$ , when  $M = P$  and  $M = E$ , respectively).

Obviously, the system wishes to *maximize* the social cost.

**Definition 2.2** For model  $M$ ,  $M = \{P, E\}$ , the **price of anarchy**,  $r(M)$  is

$$r(M) = \max_{\Pi_M(G), \mathbf{s}} \frac{\max_{\mathbf{s}^* \in \mathcal{S}} SC(\Pi_M(G), \mathbf{s}^*)}{SC(\Pi_M(G), \mathbf{s})}$$

### 3 The Edge Model

We first study Nash equilibria in the Edge model.

#### 3.1 $r$ -Factor, Regular, Perfect Matching Graphs

**Theorem 3.1** For a positive integer  $r$ , an  $r$ -factorizable graph  $G$  admits a Nash equilibrium  $\mathbf{s}$  that can be computed in time  $O(T(G))$ , where  $O(T(G))$  is the time needed for the computation of an  $r$ -factor of  $G$ . Also,  $SC(\Pi_E(G), \mathbf{s}) = \frac{2\nu}{|V|}$ .

**Proof.** From  $G$  first compute in polynomial time  $O(T(G))$  an  $r$ -regular factor of  $G$ ,  $G_r(V, E_r)$ . Then construct the following configuration  $\mathbf{s}$  on  $\Pi_E(G)$ :

For each vertex player  $i \in \mathcal{N}_{vp}$ , and each vertex  $v \in V$ , set  $s_i(v) := \frac{1}{|V|}$ .

For each edge  $e \in E_r$ , set  $s_{ep}(e) := \frac{1}{|E_r|}$  and  $s_{ep}(e) := 0$  for each edge  $e \in E \setminus E_r$ .

Note first that  $\mathbf{s}$  is constructed in constant time. We now show that  $\mathbf{s}$  is a Nash equilibrium. For any vertex  $v \in V (= \text{Support}_{vp}(\mathbf{s}))$ ,

$$\begin{aligned} & P_{\mathbf{s}}(\text{Hit}(v)) \\ &= \sum_{e \in \text{Edges}_v(\mathbf{s})} s_{ep}(e) \\ &= \frac{|\text{Edges}_v(\mathbf{s})|}{|E_r|} \quad (\text{since } s_{ep} = \frac{1}{|E_r|}, \text{ for each } e \in \text{Support}_{ep}(\mathbf{s}), \text{ by construction}) \\ &= \frac{r}{\frac{r \cdot |V|}{2}} \quad (\text{since } \Delta_{G(\text{Support}_{ep}(\mathbf{s}))}(v) = r \text{ and } |E_r| = \frac{r \cdot |V|}{2} ) \\ &= \frac{2}{|V|}. \end{aligned}$$

It follows that  $P_{\mathbf{s}}(\text{Hit}(v)) = \min_{v' \in V} P_{\mathbf{s}}(\text{Hit}(v'))$ , for any vertex  $v \in \text{Support}_{vp}(\mathbf{s})$ . Thus,  $\mathbf{s}$  satisfies Condition (1) in the characterization of Nash equilibria (Theorem 2.1). For condition (2), consider any edge  $e = (u, v) \in E$ . Then,

$$\begin{aligned} & VP_e(\mathbf{s}) \\ &= VP_u(\mathbf{s}) + VP_v(\mathbf{s}) \\ &= \sum_{i \in \mathcal{N}_{vp}} (s_i(u) + s_i(v)) \\ &= 2 \cdot \nu \cdot \frac{1}{|V|}, \quad (\forall v \in V, v \in \text{Support}_{vp}(\mathbf{s}) \text{ and } s_i(v) = \frac{1}{|V|}, \text{ by construction}) \end{aligned}$$

It follows that  $\text{VP}_e(\mathbf{s}) = \max_{e' \in E} \text{VP}_{e'}(\mathbf{s})$ , for each edge  $e \in \text{Support}_{ep}(\mathbf{s})$ . Thus,  $\mathbf{s}$  satisfies Condition (2) in the characterization of Nash equilibria (Theorem 2.1), which proves that it is a Nash equilibrium.

We finally compute the social cost of  $\mathbf{s}$ :

$$\begin{aligned} & \text{SC}(\Pi_E(G), \mathbf{s}) \\ &= \text{IP}_{ep}(\mathbf{s}) \\ &= \text{VP}_e(\mathbf{s}), \quad (\text{for any edge } e \in \text{Support}_{ep}(\mathbf{s}), \text{ since } \mathbf{s} \text{ is a Nash equilibrium}) \\ &= \frac{2\nu}{|V|}, \end{aligned}$$

as required. ■

**Corollary 3.2** *For a positive integer  $r$ , a polynomially computable  $r$ -factorizable graph  $G$  has a polynomially computable Nash equilibrium.*

**Corollary 3.3** *A regular graph has a polynomially computable Nash equilibrium.*

Observe that the class of  $r$ -factorizable graphs is a subclass for  $(r-1)$ -factorizable graphs. So, we can restrict ourselves to the easiest case of 1-factorizable graphs (Perfect Matching graphs). Such a graph can be recognized in polynomial time  $O\left(\sqrt{|V||E|} \cdot \log_{|V|} \frac{|V|^2}{|E|}\right)$  (3); and a Perfect Matching of it can be computed in the same time. Thus, Theorem 3.1 implies that,

**Corollary 3.4** *If  $G$  is a Perfect Matching graph, then it admits a Nash equilibrium that can be computed in time  $O\left(\sqrt{|V||E|} \cdot \log_{|V|} \frac{|V|^2}{|E|}\right)$ .*

### 3.2 Trees

In this section we consider trees. We present an efficient algorithm to compute a mixed Nash equilibrium in a tree. The algorithm, called **TreesNE**, is presented in pseudocode in Figure 3.2.

**Theorem 3.5** *Algorithm **TreesNE** computes a mixed Nash equilibrium of a tree graph  $T = (V, E)$  in linear time  $O(|V|)$ .*

**Proof.** We prove the claim via a sequence of Lemmas.

**Lemma 3.6** *Set  $VC$  is an Independent Set.*

**Proof.** Set  $VC$  is constructed during Step (2) of the algorithm. We prove that the set is an Independent Set by induction to the number of iterations of the step. Consider an iteration  $r$  and denote as  $T'_r$  and  $VC_r$  the current graph  $T'$  and vertex set  $VC$ , respectively. In the first iteration of the step, set  $VC$  is extended with the leaves of tree  $T'_r$ ,  $\text{leaves}(T'_r)$ . Since for the first iteration,  $\text{leaves}(T') = \text{leaves}(T)$ , it follows that initially, set  $VC_r$  is an Independent Set.

Assume, by induction, that  $VC_r$  is an Independent Set at the beginning of iteration  $r$ . We prove that this remains true after the extension of the set at the



**Algorithm TreesNE**INPUT: A rooted tree  $T = (V, E)$ OUTPUT: A mixed Nash equilibrium  $\mathbf{s}$  for  $T$ .

- (1) Set  $T' := T$  and  $VC := \emptyset$ .
- (2) Repeat until  $T' == \emptyset$ 
  - (2/a) Set  $VC := VC \cup \text{leaves}(T')$ .
  - (2/b) For each vertex  $v \in \text{leaves}(T')$ ,
    - If  $\text{parent}_{T'}(v) \neq \emptyset$ , then  $EC := EC \cup \{(v, \text{parent}_{T'}(v))\}$
    - else  $EC := EC \cup \{(v, u)\}$ , for any  $u \in \text{children}_{T'}(v)$ .
  - (2/c) Set  $T' := T' \setminus \{\text{leaves}(T'), \text{parents}(\text{leaves}(T'))\}$ .
- (3) Set  $\text{Support}_{ep}(\mathbf{s}) := EC$  and  $\text{Support}_{vp}(\mathbf{s}) := VC$ .
- (3) For each vertex player  $i \in \mathcal{N}_{vp}$ , and each vertex  $v \in VC$ , set  $s_i(v) = \frac{1}{|VC|}$ .  
For each edge  $e \in EC$ , set  $s_{ep}(e) = \frac{1}{|EC|}$ .

end of the iteration. Consider a vertex  $v \in \text{leaves}(T'_r)$ . Since  $r > 1$ , vertex  $v$  is an inner vertex of the graph  $T$ . Moreover, by Step (2/c), in each expansion of set  $VC$ , we exclude from the set the parents of the currently inserted vertices. It follows that vertex set  $\text{children}_T(v)$  has been excluded from the set  $VC_r$ , in previous iterations of the step. As it concerns the parent of  $v$  in  $T$ , we argue that  $\text{parent}_T(v)$  is not contained in  $VC_r$ . This is true because, by Step (2/a), in each iteration,  $VC_r$  is expanded only with the leaves of  $T_r$ . It follows that  $\text{parent}_T(v)$  can not be contained in  $VC_r$ . Thus, extending set  $VC$  with set  $\text{leaves}(T'_r)$ , in current iteration, guarantees that the set is still an Independent Set, as required. ■

**Lemma 3.7** *Set  $EC$  is an Edge Cover.*

**Proof.** Note that each vertex  $v \in V$  is considered in Step (2) of the algorithm, either as a (i) leaf of  $T'$  or (ii) a parent of such a leaf. In both cases, an edge  $(v, u)$  is added to  $EC$  (in Step (2/b)), where  $u$  is the parent of vertex  $v$ , for case (i) or  $u$  is one of its children, for case (ii). Thus, in any case, vertex  $v$  is covered by  $EC$  so that  $EC$  is an Edge Cover. ■

**Lemma 3.8** *Set  $VC$  is a Vertex Cover of  $T(EC)$ .*

**Proof.** For each edge  $(v, u)$  added to  $EC$  (at Step (2/b) of the algorithm), vertex  $v \in \text{leaves}(T')$  was added to  $VC$  (at Step (2/a) of the same iteration of the algorithm). The claim follows. ■

**Lemma 3.9** *Profile  $\mathbf{s}$  is an Independent Covering profile.*

**Proof.** We first show that  $\mathbf{s}$  is a Covering profile. By Lemma 3.7,  $EC$  is an Edge Cover. By Step (3) of the algorithm,  $\text{Support}_{ep}(\mathbf{s}) = EC$ . It follows that

$\text{Support}_{ep}(\mathbf{s})$  is an Edge Cover, as required by Condition (1) of a Covering profile. By Lemma 3.8,  $VC$  is a Vertex Cover of  $T(EC)$ . By Step (3) of the algorithm,  $\text{Support}_{ep}(\mathbf{s}) = EC$  and  $\text{Support}_{vp}(\mathbf{s}) = VC$ . It follows that  $\text{Support}_{vp}(\mathbf{s})$  is a Vertex Cover of the graph  $T(\text{Support}_{ep}(\mathbf{s}))$ , as required by Condition (2) of a Covering profile. Thus,  $\mathbf{s}$  is a Covering profile.

We proceed to show that  $\mathbf{s}$  is an Independent Covering profile. Note first that  $\mathbf{s}$  is a uniform profile such that  $s_i = s_j$ , for any two vertex players  $i, j \in \mathcal{N}_{vp}$ . By Lemma 3.6, and since  $\text{Support}_{vp}(\mathbf{s}) = VC$ , it follows that  $\text{Support}_{vp}(\mathbf{s})$  is an Independent Set. Thus,  $\mathbf{s}$  satisfies additional Condition (1) of an Independent Covering profile.

We proceed to prove additional Condition (2) of an Independent Covering profile. Note that, by Step (2/b) of the algorithm, for each vertex  $v$  added in  $VC$ , we add an edge  $(v, u)$  in  $EC$ , where either  $u = \text{parent}_{T'}(v)$  or  $u \in \text{children}_T(v)$  (in the case where  $\text{parent}_{T'}(v) = \emptyset$ ). By Condition (1) of a Covering profile, there exists at least one edge  $(v, u) \in \text{Support}_{ep}(\mathbf{s})$ . We claim that there is exactly one such edge. Note that, vertex  $v$  is either a leave of  $T$  or an inner vertex of  $T$ . In the first case, edge  $(v, u)$  is the only incident to  $v$  edge in  $T$ ; thus the claim follows. For the latter case, since  $v \in \text{leaves}(T')$ , Step (2/c) implies that  $\text{children}_T(v)$  have been removed from  $T'$  in previous iterations of the algorithm. Thus, edge  $(v, u)$ , such that  $u \in \text{children}_T(v)$  are not contained in  $\text{Support}_{ep}(\mathbf{s})$ . Thus, edge  $(v, u)$ , such that  $u \in \text{children}_T(v)$  are not contained in  $\text{Support}_{ep}(\mathbf{s})$ . Since,  $T$  is a tree, it follows that edge  $(v, u) \in \text{Support}_{ep}(\mathbf{s})$  is the only one edge of  $\text{Support}_{ep}(\mathbf{s})$  incident to vertex  $v \in \text{Support}_{vp}(\mathbf{s})$ . Additional Condition (2) of an Independent Covering profile follows, concluding the claim. ■

We now return in the proof of the Theorem. Lemma 3.9 implies that  $\mathbf{s}$  is an Independent Covering profile. Thus, by Theorem 2.3,  $\mathbf{s}$  is a Nash equilibrium, as required.

For the time complexity of the algorithm, Step (1) takes constant time. Step (2) iterates at most  $O(|V|)$  times. In each iteration, Steps (2/a), (2/c) takes constant time. By Step (2/b), each vertex  $v \in V$  is considered in exactly one iteration of Step (2). Moreover, Step (2/b) takes constant time. Thus, Step (2) is completed in linear time  $O(|V|)$ . Step (3) takes constant time. Finally, Step (4) takes  $O(|V|)$  time. It follows that the algorithm is completed in linear time  $O(|V|)$ . ■

### 3.3 The Price of Anarchy

We first upper and lower bound the Social Cost of a Nash equilibrium.

**Theorem 3.10** *For a Nash equilibrium  $\mathbf{s}$ ,*

$$\frac{\nu}{\min \{|\text{Support}_{ep}(\mathbf{s})|, |\text{Support}_{vp}(\mathbf{s})|\}} \leq \text{SC}(\Pi_E(G), \mathbf{s}) \leq \frac{\nu \cdot \Delta_G(\text{Support}_{ep}(\mathbf{s}))}{|\text{Support}_{ep}(\mathbf{s})|}.$$

**Proof.** We first show the lower bound.



$$\begin{aligned}
& \max_{e' \in E} \text{VP}_{e'}(\mathbf{s}) \\
= & \frac{1}{|\text{Support}_{ep}(\mathbf{s})|} \cdot \sum_{e \in \text{Support}_{ep}(\mathbf{s})} \text{VP}_e(\mathbf{s}) \quad (\text{by Condition (2) of Theorem 2.1}). \\
= & \frac{1}{|\text{Support}_{ep}(\mathbf{s})|} \cdot \sum_{v \in \text{Vertices}_G(\text{Support}_{ep}(\mathbf{s}))} |\text{Edges}_v(\mathbf{s})| \cdot \text{VP}_v(\mathbf{s}) \\
= & \frac{1}{|\text{Support}_{ep}(\mathbf{s})|} \cdot \sum_{v \in V} |\text{Edges}_v(\mathbf{s})| \cdot \text{VP}_v(\mathbf{s}),
\end{aligned}$$

since profile  $\mathbf{s}$  is a Covering profile (by Proposition 2.2), it satisfies Condition (1) of Covering profile, i.e.  $\text{Support}_{ep}(\mathbf{s})$  is an Edge Cover of  $G$ . So,

$$\begin{aligned}
& \max_{e' \in E} \text{VP}_{e'}(\mathbf{s}) \\
\geq & \frac{1}{|\text{Support}_{ep}(\mathbf{s})|} \cdot \sum_{v \in V} \text{VP}_v(\mathbf{s}) \\
= & \frac{\nu}{|\text{Support}_{ep}(\mathbf{s})|}.
\end{aligned}$$

Thus,

$$\begin{aligned}
& \text{SC}(\Pi_E(G), \mathbf{s}) \\
= & \text{IP}_{ep}(\mathbf{s}) \\
= & \text{VP}_e(\mathbf{s}) \quad (\text{for an edge } e \in \text{Support}_{ep}(\mathbf{s}), \text{ since } \mathbf{s} \text{ is a Nash equilibrium}) \\
= & \max_{e' \in E} \text{VP}_{e'}(\mathbf{s}) \quad (\text{by Condition (2) of Theorem 2.1}) \\
\geq & \frac{\nu}{|\text{Support}_{ep}(\mathbf{s})|}.
\end{aligned}$$

Also, we argue that since  $\mathbf{s}$  is a Nash equilibrium, there exists a vertex  $v' \in \text{Support}_{vp}(\mathbf{s})$  such that  $\text{VP}_{v'}(\mathbf{s}) \geq \frac{\nu}{|\text{Support}_{vp}(\mathbf{s})|}$ . Assume in contrary that,  $\text{VP}_v(\mathbf{s}) < \frac{\nu}{|\text{Support}_{vp}(\mathbf{s})|}$ , for each vertex  $v \in \text{Support}_{vp}(\mathbf{s})$ . Then,

$$\begin{aligned}
& \sum_{v \in V} \text{VP}_v(\mathbf{s}) \\
= & \sum_{v \in \text{Support}_{vp}(\mathbf{s})} \text{VP}_v(\mathbf{s}) \\
< & |\text{Support}_{vp}(\mathbf{s})| \cdot \frac{\nu}{|\text{Support}_{vp}(\mathbf{s})|} \\
< & \nu,
\end{aligned}$$

a contradiction since,  $\sum_{v \in V} \text{VP}_v(\mathbf{s}) = \nu$  (since  $\mathbf{s}$  is a profile).

It follows that there exists a vertex  $v' \in \text{Support}_{vp}(\mathbf{s})$  such that  $\text{VP}_{v'}(\mathbf{s}) \geq \frac{\nu}{|\text{Support}_{vp}(\mathbf{s})|}$ .

□

Thus,

$$\begin{aligned}
 & \text{SC}(\Pi_E(G), \mathbf{s}) \\
 = & \quad \text{IP}_{ep}(\mathbf{s}) \\
 = & \quad \text{VP}_{e'}(\mathbf{s}) \\
 & \quad \text{(for an edge } e' = (v', u) \in \text{Support}_{ep}(\mathbf{s}), \text{ since } \mathbf{s} \text{ is a Nash equilibrium)} \\
 = & \quad \text{VP}_{v'}(\mathbf{s}) + \text{VP}_u(\mathbf{s}) \\
 \geq & \quad \text{VP}_{v'}(\mathbf{s}) \\
 \geq & \quad \frac{\nu}{|\text{Support}_{vp}(\mathbf{s})|} \quad \text{(by definition of vertex } v'),
 \end{aligned}$$

as required.

It follows that,

$$\text{SC}(\Pi_E(G), \mathbf{s}) \geq \frac{\nu}{\min \{|\text{Support}_{ep}(\mathbf{s})|, |\text{Support}_{vp}(\mathbf{s})|\}}.$$

We now prove the upper bound.

$$\begin{aligned}
 & \sum_{e \in \text{Support}_{ep}(\mathbf{s})} \text{VP}_e(\mathbf{s}) \\
 = & \quad \sum_{v \in \text{Vertices}_G(\text{Support}_{ep}(\mathbf{s}))} |\text{Edges}_v(\mathbf{s})| \cdot \text{VP}_v(\mathbf{s}) \\
 = & \quad \sum_{v \in V} |\text{Edges}_v(\mathbf{s})| \cdot \text{VP}_v(\mathbf{s}) \\
 \leq & \quad \sum_{v \in V} \Delta(G(\text{Support}_{ep}(\mathbf{s}))) \cdot \text{VP}_v(\mathbf{s}) \\
 = & \quad \Delta(G(\text{Support}_{ep}(\mathbf{s}))) \cdot \sum_{v \in V} \text{VP}_v(\mathbf{s}) \\
 \leq & \quad \Delta(G(\text{Support}_{ep}(\mathbf{s}))) \cdot \nu \quad \text{(s is a profile)}
 \end{aligned}$$

So,

$$\begin{aligned}
 & \max_{e' \in E} \text{VP}_{e'}(\mathbf{s}) \\
 = & \quad \frac{1}{|\text{Support}_{ep}(\mathbf{s})|} \cdot \sum_{e \in \text{Support}_{ep}(\mathbf{s})} \text{VP}_e(\mathbf{s}) \quad \text{(by Condition (2) of Theorem 2.1)} \\
 = & \quad \frac{\Delta(G(\text{Support}_{ep}(\mathbf{s}))) \cdot \nu}{|\text{Support}_{ep}(\mathbf{s})|}
 \end{aligned}$$

Thus,

$$\begin{aligned}
 & \text{SC}(\Pi_E(G), \mathbf{s}) \\
 = & \quad \text{IP}_{ep}(\mathbf{s}) \\
 = & \quad \text{VP}_e(\mathbf{s}) \\
 & \quad \text{(for an edge } e \in \text{Support}_{ep}(\mathbf{s}), \text{ since } \mathbf{s} \text{ is a Nash equilibrium)} \\
 = & \quad \max_{e' \in E} \text{VP}_{e'}(\mathbf{s}) \quad \text{(by Condition (2) of Theorem 2.1)} \\
 \leq & \quad \frac{\Delta(G(\text{Support}_{ep}(\mathbf{s}))) \cdot \nu}{|\text{Support}_{ep}(\mathbf{s})|}.
 \end{aligned}$$

The proof is now complete. ■

We provide an estimation on the payoffs of the vertex players in any Nash equilibrium.

**Lemma 3.11** *In a mixed Nash equilibrium  $\mathbf{s}$ ,*

$$1 - \frac{2}{|\text{Support}_{vp}(\mathbf{s})|} \leq \text{IP}_i(\mathbf{s}) \leq 1 - \frac{1}{|\text{Support}_{vp}(\mathbf{s})|}.$$

**Proof.** For any vertex player  $i \in \mathcal{N}_{vp}$ ,

$$\begin{aligned} & \text{IP}_i(\mathbf{s}) \\ = & \frac{1}{|\text{Support}_{vp}(\mathbf{s})|} \cdot \sum_{v \in \text{Support}_{vp}(\mathbf{s})} \text{IP}_i(\mathbf{s}) \\ = & \frac{1}{|\text{Support}_{vp}(\mathbf{s})|} \cdot \sum_{v \in \text{Support}_{vp}(\mathbf{s})} \left( 1 - \sum_{e \in \text{Edges}_s(v)} s_{ep}(e) \right) \\ = & \frac{1}{|\text{Support}_{vp}(\mathbf{s})|} \cdot \sum_{v \in \text{Support}_{vp}(\mathbf{s})} (1 - \sum_{e \in \text{Edges}_s(v)} s_{ep}(e)) \end{aligned}$$

Since  $\mathbf{s}$  is a Covering profile (Proposition 2.2),  $\text{Support}_{vp}(\mathbf{s})$  is a vertex cover of  $\text{Support}_{ep}(\mathbf{s})$ . Therefore, any edge  $e \in \text{Support}_{ep}(\mathbf{s})$  appears either at most twice in the the second right sum  $\sum_{v \in \text{Support}_{vp}(\mathbf{s})}$ , once for each of its endpoints. So,

$$\begin{aligned} & \text{IP}_i(\mathbf{s}) \\ \geq & \frac{1}{|\text{Support}_{vp}(\mathbf{s})|} \cdot \left( |\text{Support}_{vp}(\mathbf{s})| - 2 \sum_{e \in \text{Support}_{ep}(\mathbf{s})} s_{ep}(e) \right) \\ & \quad \text{(since } \sum_{e \in \text{Support}_{ep}(\mathbf{s})} s_{ep}(e) = 1) \\ = & 1 - \frac{2}{|\text{Support}_{vp}(\mathbf{s})|}, \end{aligned}$$

as required.

Moreover, any edge  $e \in \text{Support}_{ep}(\mathbf{s})$  appears either at least once in the the second right sum  $\sum_{v \in \text{Support}_{vp}(\mathbf{s})}$ , for one of the two end points of edge  $e$ . So,

$$\begin{aligned} & \text{IP}_i(\mathbf{s}) \\ \leq & \frac{1}{|\text{Support}_{vp}(\mathbf{s})|} \cdot \left( |\text{Support}_{vp}(\mathbf{s})| - 1 \sum_{e \in \text{Support}_{ep}(\mathbf{s})} s_{ep}(e) \right) \\ & \quad \text{(since } \sum_{e \in \text{Support}_{ep}(\mathbf{s})} s_{ep}(e) = 1) \\ = & 1 - \frac{1}{|\text{Support}_{vp}(\mathbf{s})|}, \end{aligned}$$

as required. The claims follows.  $\blacksquare$

**Theorem 3.12** *For the Edge model,  $\frac{|V|}{2} \leq r(\mathbf{E}) \leq |V|$ .*

**Proof.** We first prove the upper bound. Obviously,  $\max_{\mathbf{s}^* \in \mathcal{S}} \text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}^*) \leq \nu$ . Now consider the following profile  $\mathbf{s}'$ : Set each vertex player  $i \in \mathcal{N}_{vp}$ ,  $s'_i = v$ , for some vertex  $v \in V$  and set  $s'_{ep} = (v, u)$ , for some  $(v, u) \in E$  such that  $u \in \text{Neigh}_G(v)$ . Then,  $\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}^*) = \text{IP}_{ep}(\mathbf{s}') = \nu$ . It follows that,  $\max_{\mathbf{s}^* \in \mathcal{S}} \text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}^*) = \nu$ .

So,

$$\begin{aligned}
 & r(\mathbf{E}) \\
 = & \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \frac{\max_{\mathbf{s}^* \in \mathcal{S}} \text{SC}(\Pi_{\mathbf{M}}(G), \mathbf{s}^*)}{\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s})} \\
 = & \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \frac{\nu}{\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s})} && (\text{since } \text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}') = \nu) \\
 \leq & \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \frac{\nu}{\min\{|\text{Support}_{ep}(\mathbf{s})|, |\text{Support}_{vp}(\mathbf{s})|\}} && (\text{by Theorem 3.10}) \\
 \leq & \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \{\min\{|\text{Support}_{ep}(\mathbf{s})|, |V(\text{Support}_{vp}(\mathbf{s}))|\}\} \\
 \leq & \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \{|V(\text{Support}_{vp}(\mathbf{s}))|\}
 \end{aligned}$$

The last inequality is true because  $\max\{\min\{f_1, f_2\}\} \leq \max\{f_1\}$ , where  $f_1, f_2$  are any two functions. So,

$$\begin{aligned}
 r(\mathbf{E}) & \leq \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \{|V(\text{Support}_{vp}(\mathbf{s}))|\} \\
 & \leq |V| && (\text{since } |\text{Support}_{vp}(\mathbf{s})| \leq |V|).
 \end{aligned}$$

We proceed to show the lower bound. Note that Theorem 3.3 implies that there exists an instance  $\Pi_{\mathbf{E}}(G)$  and a profile  $\mathbf{s}'$  such that  $\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}') = \frac{2\nu}{|V|}$ . Thus,

$$\begin{aligned}
 & r(\mathbf{E}) \\
 = & \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \frac{\max_{\mathbf{s}^* \in \mathcal{S}} \text{SC}(\Pi_{\mathbf{M}}(G), \mathbf{s}^*)}{\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s})} \\
 = & \max_{\Pi_{\mathbf{E}}(G), \mathbf{s}} \frac{\nu}{\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s})} && (\text{since } \text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}^*) = \nu) \\
 \geq & \frac{\nu}{\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}')} && (\text{by definition of profile } \mathbf{s}') \\
 \geq & \frac{\nu}{\frac{2\nu}{|V|}} && (\text{SC}(\Pi_{\mathbf{E}}(G), \mathbf{s}') = \frac{2\nu}{|V|}, \text{ by Theorem 3.3}) \\
 = & \frac{|V|}{2},
 \end{aligned}$$

as required. ■

#### 4 The Path Model

For the Path model, we characterize pure Nash Equilibria. We first prove:

**Proposition 4.1** *If  $\Pi_{\mathbf{P}}(G)$  admits a pure Nash equilibrium  $\mathbf{s}$  then the graph  $G$  is Hamiltonian.*

**Proof.** Consider the path  $w \in \text{Paths}(G)$  such that  $s_{pp}(w) = 1$ . We prove that  $w$  is a Hamiltonian path so that  $G$  is Hamiltonian. Assume in contrary that  $G$  does not contain a Hamiltonian path. Then,  $\text{Vertices}_G(w) \subset V$ .  $P_{\mathbf{s}}(\text{Hit}(v)) = \sum_{w \in \text{Paths}_v(\mathbf{s})} s_{pp}(w) = 1$ . On the other hand, for any vertex  $v \in V \setminus \{\text{Vertices}_G(w)\}$ ,  $P_{\mathbf{s}}(\text{Hit}(v)) = \sum_{w \in \text{Paths}_v(\mathbf{s})} s_{pp}(w) = 0$ .

Since,  $\text{IP}_i((\mathbf{s}_{-i}, v)) = 1 - P_{\mathbf{s}}(\text{Hit}(v))$ , it follows that  $\text{IP}_i((\mathbf{s}_{-i}, v)) > \text{IP}_i((\mathbf{s}_{-i}, u))$ , for any two vertices  $v, u$ , such that  $v \in V \setminus \{\text{Vertices}_G(w)\}$  and  $u \in \text{Vertices}_G(w)$ .



Since  $\mathbf{s}$  is a local maximizer for the Expected Individual Profit of the player  $vp_i$  and a pure profile, it follows that the player chooses some such  $v$  with probability 1 while he chooses any such  $u$  with probability zero. It follows that,

$$\begin{aligned} \text{IP}_{pp}(\mathbf{s}_{-pp}, w) &= \text{VP}_w(\mathbf{s}) \\ &= \sum_{v \in \text{Vertices}_G(w)} \sum_{i \in \mathcal{N}_{vp}} s_i(v) \\ &= 0. \end{aligned}$$

Consider now an alternative path  $w' \in \text{Paths}(G)$ ,  $w' \neq w$ , such that  $v \in \text{Vertices}_G(w')$  and  $v \in V \setminus \{\text{Vertices}_G(w)\}$ . (Note that for vertex  $v$ ,  $s_i(v) = 1$ ). Then,

$$\begin{aligned} \text{IP}_{pp}(\mathbf{s}_{-pp}, w') &= \text{VP}_{w'}(\mathbf{s}) \\ &= \sum_{v \in \text{Vertices}_G(w')} \sum_{i \in \mathcal{N}_{vp}} s_i(v) \\ &> 0. \end{aligned}$$

Since  $\mathbf{s}$  is a Nash equilibrium, for each strategy  $w \in S_{pp}$  such that  $s_{pp}(w) > 0$ , all Conditional Expected Individual Profits  $\text{IP}_{pp}(\mathbf{s}_{-pp}, w)$  are the same and no less than any Conditional Expected Individual Profit  $\text{IP}_{pp}(\mathbf{s}_{-pp}, w')$  with  $s_{pp}(w') = 0$ . Thus,

$$\begin{aligned} \text{IP}_{pp}(\mathbf{s}_{-pp}, w) &\geq \text{IP}_{pp}(\mathbf{s}_{-pp}, w') \\ &> 0, \end{aligned}$$

a contradiction, since  $\text{IP}_{pp}(\mathbf{s}_{-pp}, w) = 0$ . It follows that  $G$  is Hamiltonian, as required.  $\blacksquare$

Moreover, we prove:

**Theorem 4.2** *If the graph  $G$  is Hamiltonian then  $\Pi_P(G)$  admits a pure Nash equilibrium.*

**Proof.** Assume that  $G$  contains a Hamiltonian path  $w$ . Consider a pure profile  $\mathbf{s}$  such that  $s_{pp}(w) = 1$ . Then, for the path player  $pp$ ,

$$\begin{aligned} &\text{IP}_{pp}(\mathbf{s}_{-pp}, w) \\ &= \text{VP}_w(\mathbf{s}) \\ &= \sum_{v \in \text{Vertices}_G(w)} \sum_{i \in \mathcal{N}_{vp}} s_i(v) \\ &= \nu \quad (\text{since } w \text{ is a Hamiltonian path, by construction}). \end{aligned}$$

Thus, the Conditional Expected Individual Profit  $\text{IP}_{pp}(\mathbf{s}_{-pp}, w)$  of the path player is  $\text{IP}_{pp}(\mathbf{s}_{-pp}, w) \geq \text{IP}_{pp}(\mathbf{s}_{-pp}, w')$ , for any alternative strategy  $w' \in \text{Paths}(G)$ . It follows that  $\mathbf{s}$  is a local maximizer for its Expected Individual Profit.

As, it concerns the vertex players, note that for any vertex  $v \in V$ , it holds that  $v \in \text{Vertices}_G(w)$ . Thus, for any vertex player  $vp_i \in \mathcal{N}_{vp}$ ,  $P_{\mathbf{s}}(\text{Hit}(v)) = \sum_{w \in \text{Paths}_v(\mathbf{s})} s_{pp}(w) = 1$ , for any vertex  $v \in V$ . Since the Conditional Expected Individual Profit  $\text{IP}_i(\mathbf{s}_{-i}, v) = 1 - P_{\mathbf{s}}(\text{Hit}(v))$ , it follows that  $\text{IP}_i(\mathbf{s}_{-i}, v) = 0$ , for

any vertex  $v \in V$ . It follows that  $\mathbf{s}$  is a local maximizer for its Expected Individual Profit. Since  $\mathbf{s}$  is a local maximizer for the Expected Individual Profits of all players, it is a pure Nash equilibrium, as required. ■  
Propositions 4.1 and 4.2 together imply that:

**Theorem 4.3**  $\Pi_{\mathbf{P}}(G)$  admits a pure Nash equilibrium if and only if the graph  $G$  is Hamiltonian.

Theorem 4.3 immediately implies:

**Corollary 4.4** The problem of deciding whether there exists a pure NE for any  $\Pi_{\mathbf{P}}(G)$  is  $\mathcal{NP}$ -complete.

## References

- [1] Aspnes, J., Chang, K., and Yampolskiy, A. ‘Inoculation Strategies for Victims of Viruses and the Sum-of-Squares Partition Problem’, *Journal of Computer and System Sciences*, Vol. 72, No. 6, pp. 1077–1093, September 2006.
- [2] Garey, M. R., and Johnson, D. S. *Computers and Intractability: A Guide to Theory of NP-Completeness*, W. H. Freeman and Company, 1979.
- [3] Goldberg, A. V., and Karzanov, A. V. ‘Maximum Skew-Symmetric Flows’, *Proceedings of the 3rd Annual European Symposium on Algorithms*, Vol. 979, Lecture Notes in Computer Science, pp. 155–170, Springer-Verlag, September 1995.
- [4] Gelastou, M., Mavronicolas, M., Papadopoulou, V. G., Philippou, A. and Spirakis, P. ‘The Power of the Defender’, *CD-ROM Proceedings of the 2nd International Workshop on Incentive-Based Computing*, in conjunction with the 26th IEEE International Conference on Distributed Computing, July 2006.
- [5] Koutsoupias, E. and Papadimitriou, C. H., ‘Worst-Case Equilibria’, *Proceedings of the 16th International Symposium on Theoretical Aspects of Computer Science*, Vol. 1563, Lecture Notes in Computer Science, pp. 404–413, Springer-Verlag, March 1999.
- [6] Lovász, L., and Plummer, M. D. *Matching Theory*, Vol. 121, North-Holland Mathematics Studies, 1986.
- [7] Mavronicolas, M., Monien, B., and Papadopoulou, V. G. ‘How Many Attackers Can Selfish Defenders Catch?’, *CD-ROM Proceedings of the 41st Hawaii International International Conference on Systems Science*, January 2008.
- [8] Mavronicolas, M., Papadopoulou, V. G., Philippou, A. and Spirakis, P. G. ‘A Network Game with Attackers and a Defender’, *Algorithmica*, Special Issue with selected papers from the 16th Annual International Symposium on Algorithms and Computation, Vol. 51, No. 3, pp. 315–341, July 2008.
- [9] Mavronicolas, M., Papadopoulou, V. G., Persiano, G., Philippou, A., and Spirakis, P. G. ‘The Price of Defense and Fractional Matchings’, *Proceedings of*

*the 8th International Conference on Distributed Computing and Networking*, Vol. 4308, Lecture Notes in Computer Science, pp. 115–126, Springer-Verlag, December 2006.

- [10] Mavronicolas, M., Michael, L., Papadopoulou, V. G., Philippou, A. and Spirakis, P. G. ‘The Price of Defense’, *Proceedings of the 31st International Symposium on Mathematical Foundations of Computer Science*, Vol. 4162, Lecture Notes in Computer Science, pp. 717–728, Springer-Verlag, August/September 2006.
- [11] Micali, S. and Vazirani, V. V. ‘An  $O(\sqrt{VE})$  Algorithm for Finding Maximum Matching in General Graphs’, *Proceedings of the 21st Annual IEEE Symposium on Foundations of Computer Science*, pp. 17-27, 1980.
- [12] Nash, J. F., ‘Equilibrium Points in N-Person Games’, *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 36, pp. 48–49, 1950.
- [13] Nash, J. F., ‘Non-Cooperative Games’, *Annals of Mathematics*, Vol. 54, pp. 286–295, 1951.
- [14] Tutte, W. T. ‘A Short Proof of the Factor Theorem for Finite Graphs’, *Canadian Journal of Mathematics*, Vol 6, pp. 347-352, 1954.
- [15] West, D. B. *Introduction to Graph Theory*, Prentice Hall, 2nd edition, 2001.

