

# Price of Anarchy in Paving Matroid Congestion Games

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## Abstract

Congestion games allow to model competitive resource sharing in various distributed systems. Pure Nash equilibria, that are stable outcomes of a game, could be far from being socially optimal. Our goal is to identify combinatorial structures that limit the inefficiency of equilibria. This question has been mainly investigated for congestion games defined over networks. Instead, we focus on symmetric matroid congestion games, where the strategies of every player are the bases of a given matroid. We derive new upper bounds on the Price of Anarchy (PoA) of congestion games defined over  $k$ -uniform matroids and paving matroids with delay functions in class  $\mathcal{D}$ . For both affine and polynomial delay functions, our bounds indicate that the inefficiency of pure Nash equilibria is limited by these combinatorial structures.

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## 1 Introduction

Congestion games are a class of strategic games that provide an appealing paradigm to model resource sharing among selfish players. In a congestion game, a set of resources is given, and each player selects a feasible subset of the resources in order to minimize their cost function. The cost of a player's strategy is the sum of the delays of the resources selected by the player, and the delay of each resource is a function of the total number of players using it. The game is called *symmetric* if all players have the same strategy set. An example are *network congestion games*, where the resources are the arcs of a given digraph and the strategies of each player are paths in the network. Congestion games are practically relevant for various problems related to resource sharing in distributed systems, e.g., routing, network design and scheduling.

A *pure Nash equilibrium* (PNE) is a configuration where no player can decrease their cost by unilaterally deviating to another strategy, and it represents a stable outcome of the game. However, since the players act selfishly and independently in a non-cooperative fashion, a PNE might be far from minimizing the social cost, which is commonly defined as the sum of all players' costs. Two classic metrics for quantifying the inefficiency of equilibria are the *Price of Anarchy* (PoA) [18] and the *Price of Stability* (PoS) [3].

Congestion games always admit a PNE [26]. However, the complexity of computing a PNE in a congestion can be significantly affected by its combinatorial structure. While symmetric congestion games and asymmetric network congestion games are PLS-complete [13], Fabrikant et al. gave a strongly polynomial-time algorithm to find a PNE in symmetric network congestion games [13], which was later extended to symmetric totally unimodular congestion games by Del Pia et al. [12].

Our main goal is to better understand how the combinatorial structure of a congestion

game might affect the inefficiency of equilibria. For *nonatomic* congestion games, where each single player has a negligible impact on congestion, structure has no impact on the PoA. In fact, Roughgarden proved that the worst-case PoA is equal to  $\rho(\mathcal{D})$ , a function that only depends on the class  $\mathcal{D}$  of delay functions [28]. On the other hand, in *atomic* games, where each single player can affect the other players' decisions, there are structures that might reduce the inefficiency of equilibria. In the absence of structure, Awerbuch et al. [4, 5] and Christodoulou and Koutsoupias [10] independently provided an upper bound of  $5/2$  on the PoA for general atomic congestion games with affine delays. This bound can be improved to  $(5N - 2)/(2N + 1)$  if the game is symmetric [10], where  $N$  is the number of players. For atomic congestion games with polynomial delays of highest degree  $p$ , Aland et al. [2] obtained exact values for the worst-case PoA, see also [10, 4, 5]. These exact values admit a lower bound of  $\lfloor \phi_p \rfloor^{p+1}$  and an upper bound of  $\phi_p^{p+1}$ , where  $\phi_p \in \Theta(p/\ln p)$  is the unique nonnegative real solution to  $(x + 1)^p = x^{p+1}$ . In the general case, Bhawalkar et al. [6] proved that the worst-case PoA can be achieved in symmetric games.

However, in the symmetric case the PoA can significantly decrease if the players' strategy sets have a special structure. Most of the existing literature has focused on *graph* structures in network congestion games. Lücking et al. [20, 21] studied symmetric congestion games on parallel links and proved that the PoA is  $4/3$  for linear delay functions. Fotakis later extended this result to network congestion games defined over extension-parallel networks and proved that for these networks the worst-case PoA is equal to  $\rho(\mathcal{D})$ , if the delays belong to class  $\mathcal{D}$  [14]. Recently, Hao and Michini explored a further extension to the larger family of series-parallel networks. For affine delays, they proved that the worst-case PoA is in  $[27/19, 2]$  [16]; for polynomial delays of highest degree  $p$  they showed that the worst-case PoA is at most  $2^{p+1} - 1$ , which is significantly smaller than the worst-case PoA in general network congestion games [15].

In this paper we focus on another combinatorial structure, namely matroids. *Matroid congestion games* are congestion games where each player's strategy set is the set of bases of a given matroid. For this class of games, a PNE equilibrium can be efficiently computed, both in the symmetric and in the asymmetric case [1, 12]. Concerning the inefficiency of equilibria, Kleer and Schäfer [17] showed that the PoS in general matroids is upper bounded by  $\rho(\mathcal{D})$  when the delay functions belong to class  $\mathcal{D}$ . However, the PoA of matroid congestion games is not well understood. For affine delays, the worst-case PoA of general congestion games, that is equal to  $5/2$ , can be asymptotically achieved in asymmetric instances of singleton congestion games—that coincide with 1-uniform matroid congestion games—when the number of players goes to infinity [9]. Interestingly, in the symmetric case, the worst-case PoA of  $k$ -uniform matroid congestion games with affine delays cannot exceed 1.4131 and it is equal 1.35188 when the number of players goes to infinity [11]. Moreover, for symmetric  $k$ -uniform matroid congestion games with polynomial delays of highest degree  $p$  the worst-case PoA is in  $O(2^{p(p+1)})$  and in  $\Omega(2^p)$  [19]. This indicates that the combinatorial structure of  $k$ -uniform matroids significantly limits the inefficiency of equilibria. However,  $k$ -uniform matroids are very special matroids, since every subset of the ground set of size at most  $k$  is independent. *Are there weaker matroid structures that affect the inefficiency of equilibria?* In this paper we focus on *paving matroids*, i.e., matroids whose circuits have cardinality greater than or equal to the matroid rank. Unlike  $k$ -uniform matroids, paving matroids exhibit a notable predominance within the enumeration of matroids. It has been conjectured that, in an asymptotic sense, the majority of matroids are paving matroids [22]. This conjecture holds if the ground set has size at most 9 [7, 23]. Pendavingh and van der Pol [25] more recently proved that, as the size of the ground set goes to infinity, the ratio of logarithms between the

total number of matroids and the number of sparse paving matroids, a subclass of paving matroids, converges to 1.

**Our contributions.** First, we provide a lower bound of  $13/9$  on the worst-case PoA for symmetric paving matroid congestion games with affine delays. This ratio is worse than the previously known best upper bound  $\approx 1.41$  on the PoA of symmetric congestion games with affine delay functions over  $k$ -uniform matroids, which are a subclass of paving matroids. Thus, relaxing the structure of players' strategy sets from uniform matroids to paving matroids can increase the inefficiency of pure Nash equilibria.

► **Theorem 1.** *The worst-case PoA of symmetric paving matroid congestion games with affine delay functions is at least  $13/9$ .*

We next turn to the question of finding upper bounds on the PoA of symmetric paving matroid congestion games. Given the class of delay functions  $\mathcal{D}$ , we define the parameter  $z(\mathcal{D})$  as

$$z(\mathcal{D}) = \sup_{d \in \mathcal{D}, x \in \mathbb{N}^+} \frac{d(x+1)}{d(x)}.$$

Since the delay functions  $d(x)$  are non-negative and non-decreasing, we have  $z(\mathcal{D}) \geq 1$ . Our first main result is an upper bound on the worst-case PoA in symmetric paving matroid congestion games with delay functions in class  $\mathcal{D}$ .

► **Theorem 2.** *The PoA of symmetric paving matroid congestion games with delay functions in class  $\mathcal{D}$  is at most  $z(\mathcal{D})^2 \rho(\mathcal{D})$ .*

When  $\mathcal{D}$  is the class of polynomial functions of maximum degree  $p$ , we have  $z(\mathcal{D}) = 2^p$  and  $\rho(\mathcal{D}) \in \Theta(p/\ln p)$ . Thus, the worst-case PoA is in  $O(4^p p/\ln p)$ . For  $p \geq 6$  our bound is smaller than the worst-case PoA that can be achieved in general symmetric congestion games, that is in  $\Theta(p/\ln p)^{p+1}$  [2]. Thus, the worst-case PoA of symmetric congestion games *cannot* be achieved in paving matroids.

We also prove —with a substantially different approach— that this is the case for  $p = 1$ , i.e., when the delay functions are affine. In this case, the worst-case PoA for general symmetric congestion games is  $5/2$ .

► **Theorem 3.** *The PoA of symmetric paving matroid congestion games with affine delay functions is at most  $17/7$ .*

Finally, the approach used to prove Theorem 2 also provides a new upper bound on the worst-case PoA in symmetric  $k$ -uniform matroid congestion games with delay functions in class  $\mathcal{D}$ .

► **Theorem 4.** *The PoA of symmetric  $k$ -uniform matroid congestion games with delay functions in class  $\mathcal{D}$  is at most  $z(\mathcal{D})\rho(\mathcal{D})$ .*

When  $\mathcal{D}$  is the class of polynomial functions of maximum degree  $p$ , we obtain that the worst-case PoA is in  $O(2^p p/\ln p)$ . This significantly improves on the previously known upper bound of  $O(2^{p(p+1)})$  [19] and partially closes the gap with the lower bound of  $\Omega(2^p)$  [19].

## 2 Preliminaries

In this section, we first recall some basics of matroid theory and then we introduce some fundamental notions of congestion games.

**Matroids.** A *matroid* is a pair  $(R, \mathcal{I})$  where the *ground set*  $R$  consists of a finite set of elements and  $\mathcal{I}$  is a nonempty collection of subsets of  $R$  such that: (i) if  $I \in \mathcal{I}$  and  $J \subseteq I$ , then  $J \in \mathcal{I}$ ; and (ii) if  $I, J \in \mathcal{I}$  and  $|I| < |J|$ , then  $I \cup \{z\} \in \mathcal{I}$  for some  $z \in J \setminus I$ . Given a matroid  $M = (R, \mathcal{I})$ , a subset  $I$  of  $R$  is called *independent* if  $I$  belongs to  $\mathcal{I}$ , and dependent otherwise. A subset  $B \subseteq R$  is called a *basis* if  $B$  is an inclusion-wise maximal independent subset. That is,  $B \in \mathcal{I}$  and there is no  $Z \in \mathcal{I}$  with  $B \subset Z \subseteq R$ . The common size of all bases is called the *rank* of the matroid, denoted by  $r(M)$ . A *circuit* of a matroid is an inclusion-wise minimal dependent set. For every basis  $B$  and every element in  $R \setminus B$ , there is a unique circuit contained in  $B \cup \{x\}$ , that is called a *fundamental circuit*. Next, we introduce the *bijective basis-exchange property*:

► **Theorem 5** ([8]). *Let  $\mathcal{B}$  be the collection of bases of a matroid. For any  $B, B' \in \mathcal{B}$ , there is a bijection  $\pi : B \rightarrow B'$  from  $B$  to  $B'$ , such that for every  $x \in B \setminus B'$ ,  $B \setminus \{x\} \cup \{\pi(x)\}$  is a basis.*

A matroid is called *k-uniform* matroid if its independent sets are all the subsets of  $R$  of cardinality at most  $k$ , i.e. every  $k + 1$ -element subset of  $R$  is a circuit. A matroid is called *paving* matroid if every circuit of  $M$  has cardinality  $r(M)$  or  $r(M) + 1$ . The following proposition characterizes paving matroids in terms of their circuits.

► **Proposition 6** ([24]). *Let  $\mathcal{C}$  be a collection of non-empty subsets of a set  $R$  such that each member of  $\mathcal{C}$  has size either  $t$  or  $t + 1$ . Let  $\mathcal{C}' \subseteq \mathcal{C}$  consist only of the  $t$ -element members of  $\mathcal{C}$ . Then  $\mathcal{C}$  is the set of circuits of a paving matroid on  $R$  of rank  $t$  if and only if*

1. *if two distinct members  $C_1$  and  $C_2$  of  $\mathcal{C}'$  have  $t - 1$  common elements, then every  $t$ -element subset of  $C_1 \cup C_2$  is in  $\mathcal{C}'$ ; and*
2.  *$\mathcal{C} \setminus \mathcal{C}'$  consists of all the  $(t + 1)$ -element subsets of  $R$  that contains no member of  $\mathcal{C}'$ .*

**Congestion games.** We consider a congestion game with  $N$  players and resources set  $R$ . For  $n \in \mathbb{N}$ , we denote by  $[n]$  the set  $\{1, \dots, n\}$ . The set  $X^i \subseteq R$  is the strategy set of player  $i$ . We call the game *symmetric* if all the players have the same strategy set, i.e.  $X^i = X^j$  for all  $i, j \in [N]$ . A *state* of the game is a strategy profile  $s = (s^1, \dots, s^N)$  where  $s^i \in X^i$  is the strategy chosen by player  $i$ , for  $i \in [N]$ . The set of states of the game is denoted by  $X = X^1 \times \dots \times X^N$ .

For each  $r \in R$  we have a nondecreasing delay function  $d_r : [N] \rightarrow \mathbb{R}_{\geq 0}$ . Given a state  $s$  we denote the number of players using resource  $r$  by  $s_r$ . Each player using  $r$  incurs a cost equal to  $d_r(s_r)$ , i.e., the cost of  $r$  depends on the total number of players that use  $r$  in  $s$ . Since  $d_r$  is a nondecreasing function,  $d_r(j + 1) \geq d_r(j)$  for  $j \in [N - 1]$ , which models the effect of congestion. We denote the cost of a resource  $r$  with respect to state  $s$  by  $\text{cost}_s(r) = d_r(s_r)$ . We also define  $\text{cost}_s^+(r) = d_r(s_r + 1)$ . Finally, the *social cost* of state  $s$  is denoted by  $\text{cost}(s) = \sum_{r \in R} s_r d_r(s_r) = \sum_{r \in R} s_r \text{cost}_s(r)$ .

**Matroid congestion games.** A *matroid congestion game* is a congestion game where the strategy set of each player  $i$  is the set of bases  $\mathcal{B}_i$  of a given matroid  $M_i = (R_i \subseteq R, \mathcal{I}_i)$ . For an arbitrary state  $s$  of the matroid congestion game, we denote by  $B_s^i$  the strategy of player  $i$  in  $s$ . A *paving* matroid congestion game is a matroid congestion game where  $M_i$  is a paving matroid for all  $i \in [N]$ . A *k-uniform* matroid congestion game is a congestion game where  $M_i$  is a  $k$ -uniform matroid for all  $i \in [N]$  and  $k \in [\min_i |R_i|]$ .

**Pure Nash Equilibria and social optima.** A *pure Nash equilibrium* (PNE) is a state  $s = (s^1, \dots, s^i, \dots, s^N)$  such that, for each  $i \in [N]$  we have

$$\text{cost}_s(s^i) \leq \text{cost}_{\tilde{s}}(\tilde{s}^i) \quad \forall \tilde{s} = (s^1, \dots, \tilde{s}^i, \dots, s^N) \in X.$$

A PNE represents a stable outcome of the game, since no player  $i \in [N]$  can improve their cost if they select a different strategy  $\tilde{s}^i$ .

We are also interested in a *social optimum* (SO), which is a state that minimizes  $\text{cost}(s)$  over all the states  $s \in X$ . The *Price of Anarchy* (PoA) is the maximum ratio  $\frac{\text{cost}(f)}{\text{cost}(o)}$  such that  $o$  is a SO and  $f$  is a PNE. In other words, to compute the PoA we consider the “worst” PNE, i.e., a PNE whose social cost is as large as possible.

### 3 Upper bounds on the PoA for delays in class $\mathcal{D}$

In this section, our goal is to Theorems 2 and 4. To this purpose, we first introduce an auxiliary result.

► **Lemma 7.** *Consider a symmetric matroid congestion game with delays in class  $\mathcal{D}$ . Let  $f$  be a PNE, and  $o$  a SO. Let  $v$  be a resource that is not used by player  $i$  in  $f$  and let  $C_v^i$  be the unique circuit in  $B_f^i \cup \{v\}$ . Then, for all  $r \in C_v^i$  we have  $\text{cost}_f^+(r) \leq z(\mathcal{D})\text{cost}_f(r) \leq z(\mathcal{D})\text{cost}_f^+(v)$ .*

**Proof.** Assume that there exists a resource  $r \in C_v^i$  such that  $\text{cost}_f(r) > \text{cost}_f^+(v)$ . Since  $C_v^i$  is the unique circuit that satisfies  $C_v^i \setminus \{v\} \subseteq B_f^i$ , we have that  $B_f^i \setminus \{r\} \cup \{v\} \in \mathcal{B}$ , i.e., exchanging  $r$  and  $v$  defines a feasible strategy for player  $i$ . By performing this exchange player  $i$  is able to lower their cost, thus contradicting the fact that  $f$  is a PNE. Thus, we can conclude that for each  $r \in C_v^i$  we have  $\text{cost}_f(r) \leq \text{cost}_f^+(v)$ . This implies that  $z(\mathcal{D})\text{cost}_f(r) \leq z(\mathcal{D})\text{cost}_f^+(v)$ . Finally, by the definition of  $z(\mathcal{D})$ , thus we have  $\text{cost}_f^+(r) \leq z(\mathcal{D})\text{cost}_f(r)$ . ◀

For a congestion game over resource set  $R$ , we let  $G = (R, E)$  be a complete directed graph, where the nodes correspond to the resources in  $R$ . Let  $s$  and  $q$  be two states of the congestion game. We define the following two sets:

$$R^-(s, q) = \{r \in R : s_r > q_r\} \quad R^+(s, q) = \{r \in R : s_r < q_r\},$$

and we let  $l = \sum_{r \in R^-(s, q)} (s_r - q_r) = \sum_{r \in R^+(s, q)} (q_r - s_r)$ . In  $G$ , every node  $r \in R^-$  has supply  $s_r - q_r$ , and every node  $r \in R^+$  has demand  $q_r - s_r$ . A (single-commodity) flow  $F \in \mathbb{Z}^{R \times R}$  in  $G$  is a non-negative vector such that for every node  $r \in R$

$$F(\delta^-(r)) - F(\delta^+(r)) = q_r - s_r, \quad (1)$$

where  $\delta^-(r)$  contains all the arcs whose head is  $r$  and  $\delta^+(r)$  contains all the arcs whose tail is  $r$ . We call  $F$  a  $(s, q)$ -difference flow. Note that the above definitions can be applied to a generic congestion game. For a matroid congestion game, we can construct a special  $(s, q)$ -difference flow  $F$ , that we call  $(s, q)$ -exchange flow, as follows. According to Theorem 5, for each pair  $(B_s^i, B_q^i)$ , there is a bijection  $\pi^i(x) : B_s^i \rightarrow B_q^i$  such that for every  $r \in B_s^i \setminus B_q^i$  there is a unique  $\pi^i(r) \in B_q^i \setminus B_s^i$  and  $B_s^i \setminus \{r\} \cup \{\pi^i(r)\} \in \mathcal{B}$ . Starting from the zero vector, for every  $i \in [N]$ ,  $r \in B_s^i \setminus B_q^i$ , we add one unit of flow to the arc  $(r, \pi^i(r))$  to  $G$  in order to obtain  $F$ . We observe that  $F$  can be decomposed into  $l$  paths, each one starting from a node in  $R^-(s, q)$  and ending at a node in  $R^+(s, q)$ , and carrying one unit of flow.

For an arbitrary state  $q$ , consider an  $(f, q)$ -exchange flow  $F$  and any path contained in it starting from a node  $u \in R^-(f, q)$  and ending at a node  $v \in R^+(f, q)$ . If the matroid is paving, the next lemma implies that  $\text{cost}_f^+(v)$  cannot be smaller than a fraction of  $\text{cost}_f(u)$ .

► **Lemma 8.** *Suppose  $M$  is a paving matroid with  $r(M) = t \geq 1$ . Let  $q$  be an arbitrary state of the game and let  $F$  be an  $(f, q)$ -exchange flow. Let  $R^- = R^-(f, q)$  and  $R^+ = R^+(f, q)$ . For all paths  $p$  contained in  $F$  from  $u \in R^-$  to  $v \in R^+$ , and for every resource  $r$  in  $p$  we have  $\text{cost}_f(r) \leq z(\mathcal{D})^2 \text{cost}_f^+(v)$ .*

**Proof.** Let  $r^*$  be the most expensive resource of path  $p$  in  $f$ , i.e.,  $\text{cost}_f(r) \leq \text{cost}_f(r^*)$  for every resource  $r$  in  $p$ . Since  $t \geq 1$  we know that  $r^*$  is used by at least one player in  $f$ . We will prove  $\text{cost}_f(r^*) \leq z(\mathcal{D})^2 \text{cost}_f^+(v)$ . By contradiction, suppose

$$\text{cost}_f(r^*) > z(\mathcal{D})^2 \text{cost}_f^+(v). \quad (2)$$

Define

$$S = \{r \in R : \text{cost}_f^+(r) < \text{cost}_f(r^*)\}, \quad \bar{S} = \{r \in R : z(\mathcal{D})\text{cost}_f^+(r) < \text{cost}_f(r^*)\}.$$

Since  $z(\mathcal{D}) \geq 1$ , we have  $\bar{S} \subseteq S$ . Moreover, we have the following property.

▷ **Claim 9.**  $|\bar{S}| \geq t$ .

**Proof.** Since  $v$  is the last node in  $p$ , there exists a player  $j$  such that  $v \notin B_f^j$ . Let  $C_v^j$  be the fundamental circuit in  $B_f^j \cup \{v\}$ . By Lemma 7, for all  $r \in C_v^j$  we have  $\text{cost}_f^+(r) \leq z(\mathcal{D})\text{cost}_f^+(v)$ . Thus:

$$z(\mathcal{D})\text{cost}_f^+(r) \leq z(\mathcal{D})^2 \text{cost}_f^+(v) < \text{cost}_f(r^*),$$

where the last inequality comes from (2). This implies that  $C_v^j \subseteq \bar{S}$ . Since in a paving matroid of rank  $t$  every circuit has size at least  $t$  we obtain  $|\bar{S}| \geq t$ . ◁

Note that  $v \in S$ , since  $z(\mathcal{D}) \geq 1$ , and  $r^* \notin S$ . Since  $p$  traverses both  $r^*$  and  $v$ , there is an arc  $(a, b)$  in  $p$  such that  $a \notin S$  and  $b \in S$ . Since  $(a, b)$  is contained in  $F$  there exists a player  $i$  such that  $a \in B_f^i$ ,  $b \notin B_f^i$  and  $B_f^i \setminus \{a\} \cup \{b\} \in \mathcal{B}$ .

First,  $a \in B_f^i \setminus S = B_f^i \setminus (B_f^i \cap S)$ . Thus  $1 \leq t - |B_f^i \cap S|$ . We have

$$|\bar{S} \setminus B_f^i| = |\bar{S}| - |\bar{S} \cap B_f^i| \geq t - |\bar{S} \cap B_f^i| \geq t - |S \cap B_f^i| \geq t + (1 - t) = 1,$$

where the first inequality follows from Claim 9. Thus  $\bar{S} \setminus B_f^i \neq \emptyset$ . Let  $w \in \bar{S} \setminus B_f^i$ . Let  $C_w^i$  be the fundamental circuit in  $B_f^i \cup \{w\}$ . By Lemma 7 for all  $r \in C_w^i$  we have

$$\text{cost}_f^+(r) \leq z(\mathcal{D})\text{cost}_f^+(w) < \text{cost}_f(r^*),$$

where the last inequality holds because  $w \in \bar{S}$ .

This implies  $C_w^i \subseteq S$ . Recall that  $C_w^i \setminus \{w\} \subseteq B_f^i$ . Since the matroid is paving,  $|C_w^i \setminus \{w\}| \geq t - 1$ . Finally, as  $a \in B_f^i \setminus S$  we can conclude that  $B_f^i \setminus \{a\} = C_w^i \setminus \{w\} \subseteq S$ . Since  $b \in S$ , we have  $B_f^i \setminus \{a\} \cup \{b\} \subseteq S$ . We now prove that every  $t$ -element subset of  $S$  is a circuit. This immediately contradicts the fact that  $B_f^i \setminus \{a\} \cup \{b\}$  is a basis.

▷ **Claim 10.** Every  $t$ -element subset of  $S$  is a circuit of the paving matroid  $M$ .

**Proof.** Let  $h$  be a player such that  $r^* \in B_f^h$  and let  $r$  be an arbitrary resource in  $S \setminus B_f^h$ . We show that  $B_f^h \setminus \{r^*\} \cup \{r\}$  is a circuit. Consider the fundamental circuit  $C_r^h$  in  $B_f^h \cup \{r\}$ . We argue that  $r^*$  is not in  $C_r^h$ . If that was the case, we would have  $\text{cost}_f^+(r) \geq \text{cost}_f(r^*)$  by Lemma 7, which contradicts  $r \in S$ . Since we have a paving matroid  $C_r^h \geq t$ , thus  $C_r^h = \{r\} \cup B_f^h \setminus \{r^*\}$ . This proves that  $B_f^h \setminus \{r^*\}$  forms a circuit with every resource  $r \in S \setminus B_f^h$ . By applying the first statement in Proposition 6 we can conclude that every  $t$ -element subset of  $S \cup B_f^h \setminus \{r^*\}$  is a circuit. By the definition of  $S$  we have  $r^* \notin S$ , so  $S \subseteq S \cup B_f^h \setminus \{r^*\}$  and every  $t$ -element subset of  $S$  is a circuit. ◁

We recall that the function  $\rho(\mathcal{D})$ , initially introduced by Roughgarden [27], is defined as  $\rho(\mathcal{D}) := \sup_{d \in \mathcal{D}} \rho(d)$ , where

$$\rho(d) = \sup_{x \geq y \geq 0} \frac{xd(x)}{yd(y) + (x-y)d(x)}. \quad (3)$$

In the next theorem, we consider an  $(f, o)$ -exchange flow. For any  $(u, v)$ -path from  $R^-(f, o)$  to  $R^+(f, o)$ , if  $\text{cost}_f(u)$  is equal to at least a fraction  $\alpha$  of  $\text{cost}_f^+(v)$ , then we can upper bound the ratio between the social costs of  $f$  and  $o$  by  $\alpha\rho(\mathcal{D})$ .

► **Theorem 11.** *Let  $F$  be an  $(f, o)$ -exchange flow. Let  $R^- = R^-(f, o)$  and  $R^+ = R^+(f, o)$ . For all paths  $p$  contained in  $F$  from  $u \in R^-$  to  $v \in R^+$ , if  $\alpha \text{cost}_f^+(v) \geq \text{cost}_f(u)$  for some  $\alpha \geq 1$  then we have  $\text{cost}(f) \leq \alpha\rho(\mathcal{D})\text{cost}(o)$ .*

**Proof.** For every resource  $r \in R^-$ , inequality (3) and  $\alpha \geq 1$  imply

$$\begin{aligned} f_r \text{cost}_f(r) &= f_r d_r(f_r) \leq \rho(\mathcal{D})(o_r d(o_r) + (f_r - o_r)d(f_r)) \\ &\leq \rho(\mathcal{D})(\alpha o_r d(o_r) + (f_r - o_r)d(f_r)) \end{aligned} \quad (4)$$

Let  $\{p_1, \dots, p_l\}$  be an arbitrary decomposition of the flow  $F$ , where each  $p_k$  is from  $r_k^-$  to  $r_k^+$  such that  $r_k^- \in R^-$  and  $r_k^+ \in R^+$ . We have

$$\begin{aligned} \sum_{r \in R^+} (o_r - f_r) \text{cost}_o(r) &= \sum_{k=1}^l \text{cost}_o(r_k^+) \geq \sum_{k=1}^l \text{cost}_f^+(r_k^+) \\ &\geq \sum_{k=1}^l \frac{1}{\alpha} \text{cost}_f(r_k^-) = \frac{1}{\alpha} \sum_{r \in R^-} (f_r - o_r) \text{cost}_f(r), \end{aligned} \quad (5)$$

where the equalities hold by the definition of  $F$  and equality (1), the first inequality holds because of the definition of  $R^+$ , and the second inequality holds because by assumption. Let  $\bar{R} = \{r \in R : f_r = o_r\} = R \setminus (R^- \cup R^+)$ .

$$\begin{aligned} \text{cost}(f) &= \sum_{r \in R^-} f_r \text{cost}_f(r) + \sum_{r \in R^+} f_r \text{cost}_f(r) + \sum_{r \in \bar{R}} f_r \text{cost}_f(r) \\ &\leq \sum_{r \in R^-} f_r \text{cost}_f(r) + \sum_{r \in R^+} f_r \text{cost}_o(r) + \sum_{r \in \bar{R}} o_r \text{cost}_o(r) \\ &\leq \rho(\mathcal{D}) \sum_{r \in R^-} \alpha o_r \text{cost}_o(r) + \rho(\mathcal{D}) \sum_{r \in R^-} (f_r - o_r) \text{cost}_f(r) \\ &\quad + \alpha \rho(\mathcal{D}) \sum_{r \in R^+} f_r \text{cost}_o(r) + \sum_{r \in \bar{R}} o_r \text{cost}_o(r) \\ &\leq \rho(\mathcal{D}) \sum_{r \in R^-} \alpha o_r \text{cost}_o(r) + \rho(\mathcal{D}) \sum_{r \in R^+} (o_r - f_r) \text{cost}_o(r) \\ &\quad + \alpha \rho(\mathcal{D}) \sum_{r \in R^+} f_r \text{cost}_o(r) + \sum_{r \in \bar{R}} o_r \text{cost}_o(r) \\ &= \alpha \rho(\mathcal{D}) \sum_{r \in R^- \cup R^+} o_r \text{cost}_o(r) + \sum_{r \in \bar{R}} o_r \text{cost}_o(r) \leq \alpha \rho(\mathcal{D}) \text{cost}(o). \end{aligned}$$

The first inequality holds because of the definition of  $R^+$  and  $\bar{R}$ ; the second inequality holds because of inequality (4) and  $\alpha \geq 1$ ,  $\rho(\mathcal{D}) \geq 1$ ; the third inequality follows by applying (5); the last inequality follows because  $\alpha \geq 1$ ,  $\rho(\mathcal{D}) \geq 1$ . ◀

Applying Theorem 11 and Lemma 8, we can immediately derive Theorem 2.

To prove Theorem 4, we first need the following lemma, which is analogous to Lemma 8.

► **Lemma 12.** *Suppose  $M$  is a  $k$ -uniform matroid. Let  $q$  be an arbitrary state of the game. For every  $u \in R^-(f, q)$  and  $v \in R^+(f, q)$  we have  $z(\mathcal{D})\text{cost}_f^+(v) \geq \text{cost}_f(u)$ .*

**Proof.** Let  $u^*$  be the most expensive resource in  $R^-(f, q)$ , i.e.,  $\text{cost}_f(r) \leq \text{cost}_f(u^*)$  for every resource  $r \in R^-(f, q)$ . To prove the lemma, we will show that for every  $v \in R^+(f, q)$  we have  $z(\mathcal{D})\text{cost}_f^+(v) \geq \text{cost}_f(u^*)$ . By contradiction, suppose there exists a resource  $v \in R^+(f, q)$  such that

$$z(\mathcal{D})\text{cost}_f^+(v) < \text{cost}_f(u^*). \quad (6)$$

Since  $q_v > f_v$ , we have  $f_v < N$ , thus there exists at least one player  $i$  who does not use  $v$  in  $f$ , i.e.,  $v \notin B_f^i$ . We claim that, for all  $r \in B_f^i$ , we have

$$\text{cost}_f(r) \leq \text{cost}_f^+(v). \quad (7)$$

This follows from the fact that, since  $M$  is a  $k$ -uniform matroid  $B_f^i \setminus \{r\} \cup \{v\}$  is a basis of  $M$  for all  $r \in B_f^i$ . Thus, if (7) did not hold, player  $i$  could deviate from  $r \in B_f^i$  to  $v$  to decrease their cost. As a consequence,  $z(\mathcal{D})\text{cost}_f^+(v) < \text{cost}_f(u^*)$  implies that  $v \notin B_f^i$ . Moreover, recalling that  $z(\mathcal{D}) \geq 1$ , we have  $\text{cost}_f^+(r) \leq z(\mathcal{D})\text{cost}_f(r)$  for all  $r \in R$ . Combining this with (6) and (7), we obtain that, for all  $r \in B_f^i$

$$\text{cost}_f^+(r) < \text{cost}_f(u^*). \quad (8)$$

Note that (8) implies  $u^* \notin B_f^i$ . Since  $u^* \in R^-(f, q)$ ,  $f_{u^*} > o_{u^*} \geq 0$ , thus there is at least one player  $j$  using  $u^*$  in  $f$ , i.e.,  $u^* \in B_f^j$ . Since  $M$  is a  $k$ -uniform matroid,  $B_f^j \setminus \{u^*\} \cup \{r\}$  is a basis of  $M$  for all  $r \in B_f^i$ . Moreover, since  $u^* \notin B_f^i$  and  $|B_f^i| = |B_f^j| = k$ , we can conclude that  $|B_f^i \setminus B_f^j| \geq 1$ . I.e. there exists at least one resource  $r^* \in B_f^i$  such that  $r^* \notin B_f^j$ . Thus, by (8), player  $j$  could deviate from  $u^*$  to  $r^*$  to decrease their cost. This contradicts the fact that  $f$  is a PNE. ◀

Applying Theorem 11 and Lemma 12, we can immediately derive Theorem 4.

#### 4 Lower bound on the PoA of paving matroid congestion games with affine delays

In this section, we consider symmetric paving matroid congestion game with affine delays, i.e., we assume that the delay function of each resource  $r \in R$  is of the form  $d_r(x) = a_r x + b_r$  with  $a_r \geq 0$  and  $b_r \geq 0$ . Our goal is to prove Theorem 1, stating that the worst-case PoA is at least  $13/9$ . This lower bound is higher than the previously best known lower bound of  $\approx 1.35$ , which is achieved in the symmetric  $k$ -uniform matroid congestion games [11]. Moreover, this lower bound indicates that the upper bound of  $\approx 1.41$  for symmetric  $k$ -uniform matroid congestion games does not hold for paving matroids.

**Proof of Theorem 1.** We prove the theorem by constructing an instance of a symmetric paving matroid congestion game with affine delays that achieves the PoA of  $13/9$ . Let  $R = \{r_1\} \cup R_2 \cup R_3$ , where  $R_2 = \{r_2, r_3, r_4, r_5\}$  and  $R_3 = \{r_6, \dots, r_{13}\}$ . Let

$$\begin{aligned} C_1 &= \{\{r_1, r_{6+2i}, r_{6+2i+1}\} : \forall i \in \{0, 1, 2, 3\}\}, \\ C_2 &= \{S \subset R : |S| = 4 \text{ and } S' \not\subset S, \forall S' \in C_1\}. \end{aligned}$$



Let  $C = C_1 \cup C_2$ . Using Proposition 6 with  $C' = C_1$  and  $C = C$  we can easily check that  $C$  is the set of circuits for a paving matroid of rank 3 defined over  $R$ .

Next we define a symmetric congestion game over  $\mathcal{M}$ . Let the delay function of  $r_1$  be  $d_{r_1}(x) = 1$ , and for  $i \in \{2, 3, \dots, 13\}$  let  $d_{r_i}(x) = x$ . Let the number of players be  $N = 6$ . The strategy set of each player is the set of bases of the paving matroid. In a PNE, players 1 and 2 select resources  $\{r_1, r_2, r_3\}$  and for  $i \in \{3, 4, 5, 6\}$ , player  $i$  selects resources  $\{r_4, r_6, r_7\}$ ,  $\{r_4, r_8, r_9\}$ ,  $\{r_5, r_{10}, r_{11}\}$ ,  $\{r_5, r_{12}, r_{13}\}$ , respectively. Note that players will not deviate from  $r_4$  or  $r_5$  to  $r_1$ , since this would form a circuit in  $C_1$ . The social cost of this PNE state is 26. In the SO, each player  $i \in [N]$  selects resources  $\{r_1, r_{1+i}, r_{7+i}\}$ . It can be easily checked that those strategies contain no circuit and the social cost is 18. Thus, the PoA of this instance is at least  $26/18 = 13/9$ . ◀

## 5 Upper bound on the PoA of paving matroid congestion games with affine delays

In this section, we sketch the proof of Theorem 3. Consider a symmetric congestion game with  $N$  players over resource set  $R$ , and suppose that every delay function is affine. Let  $s$  and  $q$  be two arbitrary states of the game such that  $\text{cost}(s) \geq \text{cost}(q)$ , and let  $R^- = R^-(s, q)$ ,  $R^+ = R^+(s, q)$ . We consider the graph  $G$  defined in Section 3, where each node  $r \in R^-$  has supply  $s_r - q_r$  and each node  $r \in R^+$  has demand  $q_r - s_r$ , and we let  $\Phi$  be a  $(s, q)$ -difference flow in  $G$ . The following theorem identifies some special properties of  $\Phi$  that can be used to upper bound  $\frac{\text{cost}(s)}{\text{cost}(q)}$ . The proof of the theorem is deferred to the end of the section.

► **Theorem 13.** *Suppose that  $\Phi$  is an acyclic  $(s, q)$ -difference flow satisfying the following properties:*

1. For every arc  $(u, v)$  with positive flow in  $\Phi$ ,  $\text{cost}_s(u) \leq \text{cost}_s^+(v)$ .
2. For every path  $p$  from  $u \in R^-$  to  $v \in R^+$ ,  $\text{cost}_s^+(v) \geq \frac{1}{4} \text{cost}_s(u)$ .
3. Let  $(v, w)$  be an arc with positive flow in  $\Phi$ . If for every path to  $v$  starting at a node  $u \in R^-$  we have  $\text{cost}_s(v) \geq \frac{1}{2} \text{cost}_s(u)$ , then  $w \notin R^+$ .
4. For all  $r \in R^+$ ,  $s_r = 0$  and  $\Phi(\delta^+(r)) = 0$ .
5. For all  $r \notin R^+$ , the delay function of  $r$  is linear.
6. For all  $r \in R^-$ , we have  $s_r \geq \Phi(\delta^+(r))$ .

Then  $\text{cost}(s)/\text{cost}(q) \leq 17/7$ .

Now consider a symmetric paving matroid congestion game with  $N$  players over resource set  $R$ , and suppose that the delay functions  $d = (d_r)_{r \in R}$  are affine. Let  $f$  and  $o$  be a PNE and a SO, respectively, that achieve the PoA. We consider an  $(f, o)$ -exchange flow  $F$ . We then apply five steps, to map  $\mathcal{S} = (R, d, f, o, F)$  to a tuple  $\mathcal{S}' = (R', d', s, q, \Phi)$  that defines a symmetric 1-uniform matroid congestion game over  $R'$  with affine delays  $d' = (d'_r)_{r \in R'}$ , where  $s$  and  $q$  are two states of the game, and  $\Phi$  is a  $(s, q)$ -difference flow satisfying the assumptions in Theorem 13, and such that

$$\frac{\text{cost}(f)}{\text{cost}(o)} \leq \frac{\text{cost}(s)}{\text{cost}(q)}.$$

Then using Theorem 13 we can conclude that the worst-case PoA of symmetric paving matroid congestion games is at most  $17/7$ .

Let  $\mathcal{S}^0 = (R, d, f, o, F)$ . Since  $F$  is an  $(f, o)$ -exchange flow of a paving matroid congestion game, it can be verified that  $F$  satisfies properties 1 and 6. Moreover, since for affine delays  $z(\mathcal{D}) = 2$ , Lemma 8 implies that also property 2 is satisfied. We apply the following

four steps, that preserve properties 1, 2 and 6. Moreover, the construction guarantees  $\sum_{r \in R} s_r = \sum_{r \in R} q_r$  in every step. Thus, we can easily to construct a symmetric 1-uniform matroid congestion game with  $\sum_{r \in R} s_r$  players in which  $s$  and  $q$  are two states.

**Step 1.** First, we let  $s = f$ ,  $q = o$  and  $\Phi = F$ . We redefine  $(R, d, s, q, \Phi)$  as follows. For every resource  $v \in R^+(f, o)$  such that  $f_v > 0$ , we add a new resource  $v'$  with constant delay equal to  $\text{cost}_o(v)$ . We set  $s_v = q_v = f_v$ ,  $s_{v'} = 0$  and  $q_{v'} = o_v - f_v > 0$ . Note that  $q_{v'} > s_{v'}$ , i.e.,  $v' \in R^+(s, q)$ , while  $q_v = s_v$ , i.e.,  $v \notin R^+(s, q)$ . Moreover we define the flow  $\Phi$  on arc  $(v, v')$  to be  $o_v - f_v$ . At the end,  $\Phi$  is a  $(s, q)$ -difference flow that satisfies property 4

**Step 2.** For each resource  $v \in R^+(s, q)$  receiving  $t_1, \dots, t_h$  units of flow from  $h \geq 2$  resources  $u_1, \dots, u_h$  through arcs  $(u_1, v), \dots, (u_h, v)$  in  $\Phi$ , we redefine  $(R, d)$  by replacing  $v$  with  $h$  new nodes  $v_1, \dots, v_h$ , each having delay function  $d_v$ . We redefine  $(s, q)$  by setting  $s_{v_i} = 0$  and  $q_{v_i} = t_i$  for all  $i \in [h]$ . Finally, we redefine  $\Phi$  by replacing arc  $(u_i, v)$  with  $(u_i, v_i)$  having flow value  $t_i$ , for all  $i \in [h]$ . After this step, for each  $v \in R^+(s, q)$  there is only one resource sending flow to  $v$ .

**Step 3.** For each resource  $v \in R^+(s, q)$ , let  $r^*$  be the most expensive resource in  $R^-(s, q)$  that is connected to  $v$  along a path carrying at least one unit of flow in  $\Phi$ . Let  $u$  be the only resource sending flow to  $v$  in  $\Phi$ , and let  $h$  be the flow of  $\Phi$  on arc  $(u, v)$ . If  $\text{cost}_s^+(v) > \frac{1}{2}\text{cost}_s(r^*)$ , we redefine  $(R, d)$  by replacing  $v$  with  $h$  new nodes  $v_1, \dots, v_h$  having delay function  $\frac{1}{2}\text{cost}_s^+(v)x$  for  $i \in [h]$ . Moreover, we add  $h$  new resource  $w_1, \dots, w_h$  with constant delay function  $\frac{1}{2}\text{cost}_s^+(v)$  for  $i \in [h]$ . We redefine  $(s, q)$  by setting  $s_{v_i} = 1$ ,  $s_{w_i} = 0$  and  $q_{v_i} = q_{w_i} = 1$  for  $i \in [h]$ . Thus, property 4 is preserved. Finally, we redefine  $\Phi$  by setting to one the flow of arcs  $(u, v_i)$  and  $(v_i, w)$  for  $i \in [h]$ . We repeat this step until for all  $v \in R^+(s, q)$  we have  $\text{cost}_s^+(v) \leq \frac{1}{2}\text{cost}_s(r^*)$ , thus achieving property 3.

**Step 4.** For every resource  $r \notin R^+(s, q)$ , suppose  $d_r(x) = ax + b$  where  $a, b \geq 0$ . We redefine the delay function of  $r$  as  $\frac{\text{cost}_s(r)}{s_r}x = \frac{as_r + b}{s_r}x$ .

**Step 5.** We delete all the cycles in  $\Phi$  to make the flow acyclic. At the end, we set  $\mathcal{S}' = \{R, d, s, q, \Phi\}$  and  $\mathcal{S} = \mathcal{S}^0$ . Thus, we achieve property 5.

It can be easily checked that in each step of the construction the ratio  $\frac{\text{cost}(s)}{\text{cost}(q)}$  does not decrease. Based on our discussion we obtain the following lemma.

► **Lemma 14.**  $\mathcal{S}'$  satisfies the six assumptions in Theorem 13 and  $\frac{\text{cost}(f)}{\text{cost}(o)} \leq \frac{\text{cost}(s)}{\text{cost}(q)}$ .

We are now left with proving Theorem 13.

**Proof of Theorem 13.** By property 5, every node  $r \notin R^+$  has a linear delay function. Thus, for all  $r \notin R^+$  we have

$$\text{cost}_s(r) = \frac{s_r}{s_r + 1} \text{cost}_s^+(r), \quad (9)$$

$$\text{cost}_q(r) = \frac{q_r}{s_r + 1} \text{cost}_s^+(r). \quad (10)$$

Then we can write

$$1 \leq \frac{\text{cost}(s)}{\text{cost}(q)} = \frac{\sum_{r \in R \setminus R^+} s_r \text{cost}_s(r)}{\sum_{r \in R} q_r \text{cost}_q(r)} \quad (11)$$

$$= \frac{\sum_{r \in R \setminus R^+} \frac{s_r^2}{s_r + 1} \text{cost}_s^+(r)}{\sum_{r \in R \setminus R^+} \frac{q_r^2}{s_r + 1} \text{cost}_s^+(r) + \sum_{r \in R^+} q_r d_r(q_r)}, \quad (12)$$

$$\leq \frac{\sum_{r \in R \setminus R^+} \frac{s_r^2}{s_r + 1} \text{cost}_s^+(r)}{\sum_{r \in R \setminus R^+} \frac{q_r^2}{s_r + 1} \text{cost}_s^+(r) + \sum_{r \in R^+} q_r \text{cost}_s^+(r)}. \quad (13)$$

Note that equality (11) holds because we have  $s_r = 0$  for all  $r \in R^+$  according to property 4, while equality (12) is implied by (9) and (10) and inequality (13) follows from the fact that  $d_r(q_r) \geq \text{cost}_s^+(r)$  for all  $r \in R^+$ .

Let  $r \in R$ . We define  $\lambda(r) = \text{cost}_s(r) - \frac{1}{2}\text{cost}_s^+(r)$ . Let  $p = r_0, \dots, r_k$  be a path in  $\Phi$  carrying one unit of flow, where  $r_0 \in R^-$  and  $r_k \in R^+$ . For each  $h \in [k-1]$  and  $i \in [h-1]$  we define:

$$\begin{aligned}\Psi^0(p, h) &:= \left(\frac{1}{2}\right)^h \text{cost}_s(r_0), & \Psi^i(p, h) &:= \left(\frac{1}{2}\right)^i \lambda(r_{h-i}), \\ \Omega(p, 0) &:= \sum_{j=1}^{k-1} \Psi^0(p, j), & \Omega(p, i) &:= \sum_{j=i+1}^{k-1} \Psi^{j-i}(p, j) = \sum_{j=i+1}^{k-1} \left(\frac{1}{2}\right)^{j-i} \lambda(r_j).\end{aligned}$$

Moreover, we set  $\Omega(p, k-1) = 0$ ,  $\Psi(p, 0) = 0$ , and for  $h \in [k-1]$  we let  $\Psi(p, h) := \sum_{i=0}^{h-1} \Psi^i(p, h)$ . It can be checked that

$$\sum_{j=0}^{k-1} \Psi(p, j) = \sum_{j=0}^{k-1} \Omega(p, j). \quad (14)$$

▷ **Claim 15.** We have that  $\Psi(p, h) \leq \frac{1}{2}\text{cost}_s^+(r_h)$ .

*Proof.* We prove the claim by induction on  $h$ . Let  $h = 1$ . Since  $(r_0, r_1)$  is an arc in the path  $p$ , by property 1 we have

$$\Psi(p, 1) = \frac{1}{2}\text{cost}_s(r_0) \leq \frac{1}{2}\text{cost}_s^+(r_1).$$

Now assume that for  $r_h$  with  $h < k-1$ , the claim holds. Then for  $r_{h+1}$ , we have

$$\frac{1}{2}\text{cost}_s^+(r_{h+1}) \geq \frac{1}{2}\text{cost}_s(r_h) \quad (15)$$

$$= \frac{1}{2}\lambda(r_h) + \frac{1}{4}\text{cost}_s^+(r_h) \quad (16)$$

$$\geq \frac{1}{2}\lambda(r_h) + \frac{1}{2}\Psi(p, h) \quad (17)$$

$$= \frac{1}{2}\lambda(r_h) + \frac{1}{2} \left( \left(\frac{1}{2}\right)^h \text{cost}_s(r_0) + \sum_{i=1}^{h-1} \left(\frac{1}{2}\right)^i \lambda(r_{h-i}) \right) \quad (18)$$

$$= \left(\frac{1}{2}\right)^{h+1} \text{cost}_s(r_0) + \sum_{i=1}^h \left(\frac{1}{2}\right)^i \lambda(r_{h+1-i}) \quad (19)$$

$$= \Psi(p, h+1), \quad (20)$$

where (15) follows from applying property 1 to the arc  $(r_h, r_{h+1})$  in the path  $p$ , equality (16) follows from the definition of  $\lambda(r_h)$ , and inequality (17) holds because of our inductive hypothesis. ◁

Now let  $P = \{p_1, \dots, p_l\}$  be an arbitrary decomposition of the flow  $\Phi$  where each path starts at a node in  $R^-$  and ends at a node in  $R^+$  and carries one unit of flow. By property 4,  $\Phi(\delta^+(r)) = 0$  for each  $r \in R^+$ , thus in every path  $p \in P$  the only node in  $R^+$  is the sink of the path, denoted by  $t(p)$ . Moreover, for each resource  $r \in R$  we denote by  $P(r)$  the paths in  $P$  that contain  $r$  and by  $P^0(r)$  the paths in  $P$  starting at  $r$ . Finally, for each resource  $r \in R$  and path  $p \in P(r)$  we use the notation  $p(r)$  to identify the position of  $r$  in  $p$ , precisely

$p(r) = 0$  if  $r$  is the start node of  $p$ , and  $p(r) = i$  if  $r$  is the  $i$ -th node appearing after the start node of  $p$ . After summing up inequalities (14) for every path  $p \in P$  we have

$$\sum_{r \in R \setminus R^+} \sum_{p \in P(r)} \Psi(p, p(r)) = \sum_{r \in R \setminus R^+} \sum_{p \in P(r)} \Omega(p, p(r)). \quad (21)$$

For each resource  $r \in R$ , we define  $a_r := \Phi(\delta^-(r))$ ,  $b_r := \Phi(\delta^+(r)) - \Phi(\delta^-(r))$ . Note that we have  $a_r = |P(r) \setminus P^0(r)|$  and  $b_r = |P^0(r)|$  because  $\Phi$  is acyclic and thus each path  $p \in P$  is simple. For each  $r \in R \setminus R^+$  and each path in  $P(r) \setminus P^0(r)$  we apply Claim 15. Summing up we obtain

$$\Theta_r := \frac{a_r}{2} \text{cost}_s^+(r) - \sum_{p \in P(r) \setminus P^0(r)} \Psi(p, p(r)) \geq 0.$$

Since the fraction in (13) is at least 1, by subtracting the non-negative constant  $\sum_{r \in R \setminus R^+} \Theta_r$  to both the numerator and the denominator we obtain an upper bound. By using (21) and the fact that  $\Psi(p, 0) = 0$  for every  $p \in P$  we obtain

$$\frac{\text{cost}(s)}{\text{cost}(q)} \leq \frac{\sum_{r \in R \setminus R^+} A_r}{\sum_{r \in R \setminus R^+} B_r} \leq \max_{r \in R \setminus R^+} \frac{A_r}{B_r}, \quad (22)$$

where

$$A_r = \frac{(s_r)^2}{s_r + 1} \text{cost}_s^+(r) + \sum_{p \in P(r)} \Omega(p, p(r)) - \frac{a_r}{2} \text{cost}_s^+(r) \quad (23)$$

$$B_r = \frac{(q_r)^2}{s_r + 1} \text{cost}_s^+(r) + \sum_{p \in P(r)} \Omega(p, p(r)) + \sum_{p \in P^0(r)} \text{cost}_s^+(t(p)) - \frac{a_r}{2} \text{cost}_s^+(r). \quad (24)$$

In the remaining part of the proof we will show that  $\frac{A_r}{B_r} \leq \frac{17}{7}$  for all  $r \in R \setminus R^+$ .

Let  $z_r := s_r - a_r - b_r = q_r - a_r$ . Thus we have  $s_r = z_r + a_r + b_r$  and  $q_r = z_r + a_r$ . Moreover, by property 6, we have  $z_r \geq 0$  for all  $r \in R^-$ . For  $r \in R \setminus R^+$  we have  $s_r \geq q_r$ . If  $q_r = s_r$  then we have  $B_r - A_r = \sum_{p \in P^0(r)} \text{cost}_s^+(t(p)) \geq 0$ , which implies that  $\frac{A_r}{B_r} \leq 1$ . Thus, to upper bound  $\frac{A_r}{B_r}$  we now assume that  $s_r \geq q_r + 1$ , i.e.,  $r \in R^-$ . Since  $s_r = z_r + a_r + b_r$  and  $q_r = z_r + a_r$ , this implies that we have  $b_r \geq 1$ . Moreover, since  $s_r \geq 1$  we have that  $\lambda(r) = \text{cost}_s(r) - \frac{1}{2} \text{cost}_s^+(r) = (\frac{s_r}{s_r+1} - \frac{1}{2}) \text{cost}_s^+(r) \geq 0$ . This implies:

$$\Omega(p, p(r)) \geq 0 \quad \forall p \in P(r) \setminus P^0(r) \quad (25)$$

$$\Omega(p, p(r)) \geq \frac{1}{2} \lambda(r) \quad \forall p \in P(r) \setminus P^0(r) : t(p) > p(r) + 1. \quad (26)$$

Let

$$P_1^0(r) := \{p \in P^0(r) : \text{cost}_s^+(t(p)) \geq \text{cost}_s(r)\}$$

$$P_2^0(r) := \{p \in P^0(r) : \frac{1}{2} \text{cost}_s(r) \leq \text{cost}_s^+(t(p)) < \text{cost}_s(r)\}$$

$$P_3^0(r) := \{p \in P^0(r) : \frac{1}{4} \text{cost}_s(r) \leq \text{cost}_s^+(t(p)) < \frac{1}{2} \text{cost}_s(r)\}.$$

Note that we have  $P^0 = P_1^0 \cup P_2^0 \cup P_3^0$ . In fact, Lemma 8 and  $z(\mathcal{D}) = 2$  for the class of affine delay functions imply  $\text{cost}_s^+(r) \leq 4 \text{cost}_s^+(t(p))$  for every path  $p \in P^0$ .

First, recalling the definition of  $\Omega(p, 0)$  and the fact that delay functions are nonnegative, we obtain that for every path  $p \in P^0(r)$

$$\Omega(p, 0) \geq 0. \quad (27)$$

Secondly, we prove that for every path  $p \in P_2^0(r)$  we have

$$\Omega(p, 0) - \frac{1}{2}\text{cost}_s(r) \geq 0. \quad (28)$$

In fact, for every path  $p \in P_2^0(r)$ , there must exist at least one resource between  $r$  and  $t(p)$ . Otherwise  $(r, t(p))$  would be an arc in  $p$  and  $\text{cost}_s^+(t(p)) < \text{cost}_s(r)$ , which contradicts property 1. Thus, from the definition of  $\Omega(p, 0)$  and the fact that  $p$  has at least three nodes, we have  $\Omega(p, 0) \geq \frac{1}{2}\text{cost}_s(r)$ , which implies (28).

Finally, for every path  $p \in P_3^0(r)$  there must exist at least two resources between  $r$  and  $t(p)$ . Otherwise, if there is no resource between them, then  $(r, t(p))$  would be an arc in  $p$  and  $\text{cost}_s^+(t(p)) < \text{cost}_s(r)$ , which contradicts property 1. If there is one resource  $r'$  between  $r$  and  $t(p)$ , then we have two edges  $(r, r')$  and  $(r', t(p))$ . By property 1 and the definition of  $z(\mathcal{D})$  we have  $\text{cost}_s(r) \leq \text{cost}_s^+(r') \leq z(\mathcal{D})\text{cost}_s(r')$ . Since for affine delays  $z(\mathcal{D}) = 2$ , so  $\frac{1}{2}\text{cost}_s(r) \leq \text{cost}_s(r')$ . Because  $p \in P_3^0(r)$ , we also have  $\text{cost}_s^+(t(p)) < \frac{1}{2}\text{cost}_s(r) \leq \text{cost}_s(r')$ , which contradicts property 1 on the edge  $(r', t(p))$ . Thus, we have  $\Omega(p, 0) \geq (\frac{1}{2} + \frac{1}{4})\text{cost}_s(r)$  which implies

$$\Omega(p, 0) - \frac{3}{4}\text{cost}_s(r) \geq 0. \quad (29)$$

From now on we denote by  $r^*$  the most expensive resource with respect to state  $s$  among all the resources  $u \in R^-$  such that there exists a path from  $u$  to  $r$  in the directed graph induced by  $\Phi$ . We denote by  $p^*$  a path from  $r^*$  to  $r$  in this graph. Next we need to analyze the following two cases.

**Case(i):**  $\text{cost}_s(r) \leq \frac{1}{2}\text{cost}_s(r^*)$

In this case, we show that if  $\frac{A_r}{B_r} \geq 1$ , then  $\frac{A_r}{B_r} \leq \frac{7}{3}$ . We first argue that for every path  $p \in P^0(r)$ , we have

$$\text{cost}_s^+(t(p)) \geq \frac{1}{2}\text{cost}_s(r). \quad (30)$$

By contradiction, suppose there exists a path  $p \in P^0(r)$  such that  $\text{cost}_s^+(t(p)) < \frac{1}{2}\text{cost}_s(r)$ . Then, since we are assuming  $\text{cost}_s(r) \leq \frac{1}{2}\text{cost}_s(r^*)$ , we have that  $\text{cost}_s^+(t(p)) < \frac{1}{4}\text{cost}_s(r^*)$ . Then we can combine the path  $p^*$  from  $r^*$  to  $r$  and the path  $p$  from  $r$  to  $t(p)$  to obtain a path from  $r^* \in R^-$  to  $t(p) \in R^+$  that carries at least one unit of flow in  $\Phi$ . This contradicts to the property 2.

By (25) we have  $\sum_{p \in P(r) \setminus P^0(r)} \Omega(p, p(r)) \geq 0$ . Since  $A_r/B_r \geq 1$  we can subtract from both the numerator and the denominator this nonnegative constant and obtain an upper bound. Thus, by using (23) and (24) we get

$$\frac{A_r}{B_r} \leq \frac{\frac{(s_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P^0(r)} \Omega(p, 0) - \frac{a_r}{2}\text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P^0(r)} (\Omega(p, 0) + \text{cost}_s^+(t(p))) - \frac{a_r}{2}\text{cost}_s^+(r)}. \quad (31)$$

Because of inequality (30), we have  $P^0(r) = P_1^0(r) \cup P_2^0(r)$ . Thus, from (31) we obtain

$$\frac{A_r}{B_r} \leq \frac{\frac{(s_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{i=1}^2 \sum_{p \in P_i^0(r)} \Omega(p, 0) - \frac{a_r}{2}\text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{i=1}^2 \sum_{p \in P_i^0(r)} (\Omega(p, 0) + \frac{1}{2^{i-1}}\text{cost}_s(r)) - \frac{a_r}{2}\text{cost}_s^+(r)}. \quad (32)$$

To upper bound the right-hand-side of (32) we do the following. First, for every  $p \in P_1^0(r)$ , we subtract  $\Omega(p, 0) - \frac{1}{2}\text{cost}_s(r)$  from the numerator and subtract  $\Omega(p, 0)$  from the denominator. Because  $\Omega(p, 0) \geq 0$  for all  $p \in P_1^0(r)$  and  $\frac{A_r}{B_r} \geq 1$ , this will increase the right-hand-side of

inequality (32). Secondly, for every  $p \in P_2^0(r)$ , we subtract  $\Omega(p, 0) - \frac{1}{2}\text{cost}_s(r)$  from both the numerator and the denominator. This will also increase the right-hand-side of (32) because  $\Omega(p, 0) - \frac{1}{2}\text{cost}_s(r) \geq 0$  and  $\frac{A_r}{B_r} \geq 1$ . We obtain

$$\frac{A_r}{B_r} \leq \frac{\frac{(s_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P^0(r)} \frac{1}{2}\text{cost}_s(r) - \frac{a_r}{2}\text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P^0(r)} \text{cost}_s(r) - \frac{a_r}{2}\text{cost}_s^+(r)} \quad (33)$$

$$= \frac{\frac{(s_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P^0(r)} \frac{1}{2} \frac{(s_r)}{s_r+1} \text{cost}_s^+(r) - \frac{a_r}{2}\text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P^0(r)} \frac{(s_r)}{s_r+1} \text{cost}_s^+(r) - \frac{a_r}{2}\text{cost}_s^+(r)}, \quad (34)$$

where equation (34) follows from (9) and  $r \notin R^+$ . Finally, we rewrite the right-hand-side of (34) by factoring out  $\text{cost}_s^+(r)$  and exploiting  $|P^0(r)| = b_r$ ,  $s_r = a_r + b_r + z_r$ ,  $q_r = a_r + z_r$ . Next, we derive an upper bound by considering the maximum over all possible values of  $a_r, b_r$  and  $z_r$ . We obtain

$$\frac{A_r}{B_r} \leq \frac{\frac{(a_r+b_r+z_r)^2}{a_r+b_r+z_r+1} + b_r \frac{1}{2} \frac{(a_r+b_r+z_r)}{a_r+b_r+z_r+1} - \frac{a_r}{2}}{\frac{(a_r+z_r)^2}{a_r+b_r+z_r+1} + b_r \frac{(a_r+b_r+z_r)}{a_r+b_r+z_r+1} - \frac{a_r}{2}} \leq \max_{a, z \geq 0, b \geq 1} \frac{\frac{(a+b+z)^2}{a+b+z+1} + \frac{1}{2}b \frac{(a+b+z)}{a+b+z+1} - \frac{a}{2}}{\frac{(a+z)^2}{a+b+z+1} + b \frac{(a+b+z)}{a+b+z+1} - \frac{a}{2}} \leq \frac{7}{3}.$$

**Case(ii):  $\text{cost}_s(r) > \frac{1}{2}\text{cost}_s(r^*)$**  In this case, we show that if  $\frac{A_r}{B_r} \geq 1$ , then  $\frac{A_r}{B_r} \leq \frac{17}{7}$ . Let  $p$  be a path in  $P(r) \setminus P^0(r)$ . We first argue that there exists at least one resource between  $r$  and  $t(p)$  in  $p$ . By assumption we have  $\text{cost}_s(r) > \frac{1}{2}\text{cost}_s(r^*)$ , where by definition  $r^*$  is such that  $\text{cost}_s(r^*) \geq \text{cost}_s(u)$  for every resource  $u \in R^-$  such that there is a path from  $u$  to  $r$  in the directed graph induced by  $\Psi$ . Thus, property 3 implies that each arc of the form  $(r, w)$  with positive flow in  $\Phi$  has  $w \notin R^+$ . We can conclude that  $w \neq t(p) \in R^+$ . This implies  $p(t(p)) > p(r) + 1$ . By (26) we then have  $\Omega(p, p(r)) \geq \frac{1}{2}\lambda(r)$  for all  $p \in P(r) \setminus P^0(r)$ . We have

$$\frac{A_r}{B_r} = \frac{\frac{(s_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P(r)} \Omega(p, p(r)) - \frac{a_r}{2}\text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1}\text{cost}_s^+(r) + \sum_{p \in P(r)} \Omega(p, p(r)) + \sum_{p \in P^0(r)} \text{cost}_s^+(t(p)) - \frac{a_r}{2}\text{cost}_s^+(r)} \leq \frac{\frac{(s_r)^2}{s_r+1}\text{cost}_s^+(r) + \frac{1}{2}\lambda(r) + \sum_{p \in P^0(r)} \Omega(p, 0) - \frac{a_r}{2}\text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1}\text{cost}_s^+(r) + \frac{1}{2}\lambda(r) + \sum_{p \in P^0(r)} (\Omega(p, 0) + \text{cost}_s^+(t(p))) - \frac{a_r}{2}\text{cost}_s^+(r)} \quad (35)$$

$$\leq \frac{\frac{(s_r)^2}{s_r+1}\text{cost}_s^+(r) + \frac{1}{2}\lambda(r) + \sum_{i=1}^3 \sum_{p \in P_i^0(r)} \Omega(p, 0) - \frac{a_r}{2}\text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1}\text{cost}_s^+(r) + \frac{1}{2}\lambda(r) + \sum_{i=1}^3 \sum_{p \in P_i^0(r)} (\Omega(p, 0) + \frac{1}{2^{i-1}}\text{cost}_s(r)) - \frac{a_r}{2}\text{cost}_s^+(r)} \quad (36)$$

Inequality (35) holds because  $\Omega(p, p(r)) \geq \frac{1}{2}\lambda(r)$  for all  $p \in P(r) \setminus P^0(r)$  and  $\frac{A_r}{B_r} \geq 1$ . Inequality (36) holds because we have  $P^0 = P_1^0 \cup P_2^0 \cup P_3^0$ .

To derive an upper bound on the right-hand-side of (36), we do the following. First, for every  $p \in P_1^0(r)$ , we subtract  $\Omega(p, 0) - \frac{3}{4}\text{cost}_s(r)$  from the numerator and subtract  $\Omega(p, 0)$  from the denominator. Because  $\Omega(p, 0) \geq 0$  for all  $p \in P_1^0(r)$  by inequality (27) and  $\frac{A_r}{B_r} \geq 1$ , this yields an upper bound. Secondly, for every  $p \in P_2^0(r)$ , we subtract  $\Omega(p, 0) - \frac{3}{4}\text{cost}_s(r)$  from the numerator and we subtract  $\Omega(p, 0) - \frac{1}{2}\text{cost}_s(r)$  from the denominator. This will also produce an upper bound, because  $\Omega(p, 0) - \frac{1}{2}\text{cost}_s(r) \geq 0$  by inequality (28) and  $\frac{A_r}{B_r} \geq 1$ . Finally, for every  $p \in P_3^0(r)$ , we subtract  $\Omega(p, 0) - \frac{3}{4}\text{cost}_s(r)$  from both the numerator and the denominator. This will yield an upper bound because  $\Omega(p, 0) - \frac{3}{4}\text{cost}_s(r) \geq 0$  by inequality

(29) and  $\frac{A_r}{B_r} \geq 1$ . Then from (36) we have

$$\frac{A_r}{B_r} \leq \frac{\frac{(s_r)^2}{s_r+1} \text{cost}_s^+(r) + \frac{1}{2} \lambda(r) + \sum_{p \in P^0(r)} \frac{3}{4} \text{cost}_s(r) - \frac{a_r}{2} \text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1} \text{cost}_s^+(r) + \frac{1}{2} \lambda(r) + \sum_{p \in P^0(r)} \text{cost}_s(r) - \frac{a_r}{2} \text{cost}_s^+(r)} \quad (37)$$

$$= \frac{\frac{(s_r)^2}{s_r+1} \text{cost}_s^+(r) + \frac{a_r}{2} \left( \frac{s_r}{s_r+1} - \frac{1}{2} \right) \text{cost}_s^+(r) + \sum_{p \in P^0(r)} \frac{3}{4} \frac{(s_r)}{s_r+1} \text{cost}_s^+(r) - \frac{a_r}{2} \text{cost}_s^+(r)}{\frac{(q_r)^2}{s_r+1} \text{cost}_s^+(r) + \frac{a_r}{2} \left( \frac{s_r}{s_r+1} - \frac{1}{2} \right) \text{cost}_s^+(r) + \sum_{p \in P^0(r)} \frac{(s_r)}{s_r+1} \text{cost}_s^+(r) - \frac{a_r}{2} \text{cost}_s^+(r)}, \quad (38)$$

where the equation (38) follows from (9) and  $\lambda(r) = \text{cost}_s(r) - \frac{1}{2} \text{cost}_s^+(r)$ . Finally, we rewrite the right-hand-side of (38) by factoring out  $\text{cost}_s^+(r)$  and exploiting  $|P^0(r)| = b_r$ ,  $s_r = a_r + b_r + z_r$ , and  $q_r = a_r + z_r$ . Next, we derive an upper bound by considering the maximum over all possible values of  $a_r, b_r$  and  $z_r$ . We obtain

$$\frac{A_r}{B_r} \leq \frac{\frac{(a_r+b_r+z_r)^2}{a_r+b_r+z_r+1} + \frac{a_r}{2} \left( \frac{a_r+b_r+z_r}{a_r+b_r+z_r+1} - \frac{1}{2} \right) + b_r \frac{3}{4} \frac{(a_r+b_r+z_r)}{a_r+b_r+z_r+1} - \frac{a_r}{2}}{\frac{(a_r+z_r)^2}{a_r+b_r+z_r+1} + \frac{a_r}{2} \left( \frac{a_r+b_r+z_r}{a_r+b_r+z_r+1} - \frac{1}{2} \right) + b_r \frac{(a_r+b_r+z_r)}{a_r+b_r+z_r+1} - \frac{a_r}{2}} \quad (39)$$

$$\leq \max_{a, z \geq 0, b \geq 1} \frac{\frac{(a+b+z)^2}{a+b+z+1} + \frac{a}{2} \left( \frac{a+b+z}{a+b+z+1} - \frac{1}{2} \right) + \frac{3}{4} b \frac{(a+b+z)}{a+b+z+1} - \frac{a}{2}}{\frac{(a+z)^2}{a+b+z+1} + \frac{a}{2} \left( \frac{a+b+z}{a+b+z+1} - \frac{1}{2} \right) + b \frac{(a+b+z)}{a+b+z+1} - \frac{a}{2}} \leq \frac{17}{7}. \quad (40)$$

This complete the proof of the theorem.  $\blacktriangleleft$

## 6 Conclusion

We investigated the impact of matroid structures on the PoA of symmetric congestion games. We focused on paving matroids, a subclass of matroids that is conjectured to represent the vast majority of matroids. First, we proved that when the structure of strategy sets is relaxed from uniform matroids to paving matroids, the worst-case PoA increases. Moreover, for different classes of delay functions, we showed that the PoA of symmetric paving matroid congestion games can be significantly smaller than that in symmetric congestion games.

In the symmetric case, the PoA of general matroid congestion games is still not well understood. For  $N = 2$ , we can generate a symmetric congestion game with affine delays over a graphic matroid which achieves the worst-case PoA of symmetric congestion games, which is equal to  $\frac{5N-2}{2N+1} = 1.6$ . However, for larger  $N$  or different delay functions we don't know whether the the worst-case PoA of symmetric congestion games can be achieved by symmetric matroid congestion games.

Paving matroids of rank  $t$  contain circuits whose size is smaller than the circuit size of  $t$ -uniform matroids. However, the size of circuits in paving matroids can be significantly larger than that in general matroids. This suggests to further investigate how the circuit size might impact the inefficiency of equilibria in symmetric matroid congestion games. Moreover, the circuits of  $t$ -uniform matroids are highly symmetric. When dealing with paving matroids, we observed that instances with highly symmetric circuits displayed a lower PoA. On the other hand, the paving matroid congestion game example in Section 4, whose PoA is larger than the worst-case PoA of uniform matroid congestion games, has circuits that more often overlap on a single resource. In conclusion, it is open to find lower and upper bounds of symmetric matroid congestion games that depend on the size of the matroid circuits and/or on their degree of symmetry.

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**References**

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- 1 H. Ackermann, H. Röglin, and B. Vöcking. On the impact of combinatorial structure on congestion games. *J. ACM*, 55(6):25:1–25:22, Dec. 2008. ISSN 0004-5411.
- 2 S. Aland, D. Dumrauf, M. Gairing, B. Monien, and F. Schoppmann. Exact price of anarchy for polynomial congestion games. In *STACS 2006*, pages 218–229. Springer Berlin Heidelberg, Berlin, Heidelberg, 2006.
- 3 E. Anshelevich, A. Dasgupta, J. Kleinberg, E. Tardos, T. Wexler, and T. Roughgarden. The price of stability for network design with fair cost allocation. In *45th Annual IEEE Symposium on Foundations of Computer Science*, pages 295–304, 2004.
- 4 B. Awerbuch, Y. Azar, and A. Epstein. The price of routing unsplittable flow. In *Proceedings of the Thirty-Seventh Annual ACM Symposium on Theory of Computing*, STOC '05, page 57–66. Association for Computing Machinery, New York, NY, USA, 2005. ISBN 1581139608.
- 5 B. Awerbuch, Y. Azar, and A. Epstein. The price of routing unsplittable flow. *SIAM Journal on Computing*, 42(1):160–177, 2013.
- 6 K. Bhawalkar, M. Gairing, and T. Roughgarden. Weighted congestion games: Price of anarchy, universal worst-case examples, and tightness. In M. de Berg and U. Meyer, editors, *Algorithms – ESA 2010*, pages 17–28. Springer Berlin Heidelberg, Berlin, Heidelberg, 2010.
- 7 J. E. Blackburn, H. H. Crapo, and D. A. Higgs. A catalogue of combinatorial geometries. *Mathematics of Computation*, 27(121):155–s95, 1973. ISSN 00255718, 10886842.
- 8 R. A. Brualdi. Comments on bases in dependence structures. *Bulletin of the Australian Mathematical Society*, 1(2):161–167, 1969.
- 9 I. Caragiannis, M. Flammini, C. Kaklamanis, P. Kanellopoulos, and L. Moscardelli. Tight bounds for selfish and greedy load balancing. In *Proceedings of the 33rd International Conference on Automata, Languages and Programming - Volume Part I*, ICALP'06, page 311–322. Springer-Verlag, Berlin, Heidelberg, 2006. ISBN 3540359044.
- 10 G. Christodoulou and E. Koutsoupias. The price of anarchy of finite congestion games. In *Proceedings of the Thirty-Seventh Annual ACM Symposium on Theory of Computing*, STOC '05, page 67–73. Association for Computing Machinery, New York, NY, USA, 2005. ISBN 1581139608.
- 11 J. de Jong, W. Kern, B. Steenhuisen, and M. Uetz. The asymptotic price of anarchy for k-uniform congestion games. In *Approximation and Online Algorithms*, pages 317–328. Springer International Publishing, Cham, 2018.
- 12 A. Del Pia, M. Ferris, and C. Michini. Totally unimodular congestion games. In *Proceedings of the Twenty-Eighth Annual ACM-SIAM Symposium on Discrete Algorithms*, pages 577–588. SIAM, 2017.
- 13 A. Fabrikant, C. H. Papadimitriou, and K. Talwar. The complexity of pure Nash equilibria. In *Proceedings of STOC '04*, 2004.
- 14 D. Fotakis. Congestion games with linearly independent paths: Convergence time and price of anarchy. In B. Monien and U.-P. Schroeder, editors, *Algorithmic Game Theory*, pages 33–45. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008.
- 15 B. Hao and C. Michini. Inefficiency of pure nash equilibria in series-parallel network congestion games. In K. A. Hansen, T. X. Liu, and A. Malekian, editors, *Web and Internet Economics*, pages 3–20. Springer International Publishing, Cham, 2022. ISBN 978-3-031-22832-2.
- 16 B. Hao and C. Michini. The price of anarchy in series-parallel network congestion games. *Mathematical Programming*, pages 1–31, 2022.
- 17 P. Kleer and G. Schäfer. Potential function minimizers of combinatorial congestion games: Efficiency and computation. In *Proceedings of the 2017 ACM Conference on Economics and Computation*, EC '17, page 223–240. Association for Computing Machinery, New York, NY, USA, 2017. ISBN 9781450345279.
- 18 E. Koutsoupias and C. Papadimitriou. Worst-case equilibria. In *STACS 99*, pages 404–413. Springer Berlin Heidelberg, Berlin, Heidelberg, 1999.



- 19 Y. Kraakman. The price of anarchy of symmetric and semi-symmetric uniform congestion games, October 2021. URL <http://essay.utwente.nl/89018/>.
- 20 T. Lücking, M. Mavronicolas, B. Monien, and M. Rode. A new model for selfish routing. In *STACS 2004*, volume 2996 of *Lecture Notes in Computer Science*, pages 547–558. Springer Berlin Heidelberg, Berlin, Heidelberg, 2004.
- 21 T. Lücking, M. Mavronicolas, B. Monien, and M. Rode. A new model for selfish routing. *Theoretical Computer Science*, 406(3):187–206, 2008. ISSN 0304-3975. Algorithmic Aspects of Global Computing.
- 22 D. Mayhew, M. Newman, D. Welsh, and G. Whittle. On the asymptotic proportion of connected matroids. *European Journal of Combinatorics*, 32(6):882–890, 2011. ISSN 0195-6698. Matroids, Polynomials and Enumeration.
- 23 D. Mayhew and G. F. Royle. Matroids with nine elements. *Journal of Combinatorial Theory, Series B*, 98(2):415–431, 2008. ISSN 0095-8956.
- 24 J. Oxley. *Matroid Theory*. Oxford University Press, 02 2011. ISBN 9780198566946. URL <https://doi.org/10.1093/acprof:oso/9780198566946.001.0001>.
- 25 R. Pendavingh and J. van der Pol. On the number of matroids compared to the number of sparse paving matroids. *The Electronic Journal of Combinatorics*, 22(2), 2015.
- 26 R. W. Rosenthal. A class of games possessing pure-strategy Nash equilibria. *International Journal of Game Theory*, 2:65–67, 1973.
- 27 T. Roughgarden. The price of anarchy is independent of the network topology. *Journal of Computer and System Sciences*, 67(2):341 – 364, 2003. ISSN 0022-0000. Special Issue on STOC 2002.
- 28 T. Roughgarden and E. Tardos. How bad is selfish routing? *J. ACM*, 49(2):236–259, Mar. 2002. ISSN 0004-5411.