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Technical Report

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ISSN 0935–3232 · Aachener Informatik Berichte · AIB-2005-11

RWTH Aachen · Department of Computer Science · May 2005

A Counterexample to the Fully Mixed Nash Equilibrium Conjecture*

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Abstract. We study a well-known resource allocation game introduced by Koutsoupias and Papadimitriou. It was conjectured by Gairing et al. that the fully mixed Nash equilibrium is the worst Nash equilibrium for this game. The known algorithms for approximating the so-called "price of anarchy" w. r. t. mixed equilibria rely on this conjecture. We present a counterexample to the conjecture showing that fully mixed equilibria cannot be used to approximate the price of anarchy within reasonable factors.

1 The Game

Koutsoupias and Papadimitriou introduced a resource allocation game in which n jobs of size $w_1, \ldots, w_n \geq 0$ shall be assigned to m identical machines. Each job is managed by a selfish agent. The set of *pure strategies* for task i is $[m] := \{1, \ldots, m\}$. Let $(j_1, \ldots, j_n) \in [m]^n$ be a combination of pure strategies, one for each task. The *load* of link j is defined as

$$\lambda_j \;=\; \sum_{j_k = j} w_k \;\; .$$

The *cost* for agent i is λ_{j_i}. Every agent aims at minimizing her cost. The *social objective* is to minimize the maximum cost over all agents or, equivalently, the maximum load over all machines.

Agents may also use *mixed strategies*, i. e., probability distributions on the set of pure strategies. Let p_i^j denote the probability that agent i assigns its job to link j. Then

$$\mathbb{E}\left[\lambda_j\right] \;=\; \sum_{i \in [n]} w_i \, p_i^j \;\; .$$

The social cost of a mixed strategy profile $\mathbf{P} = (p_i^j)$ is defined as

$$SC(\mathbf{P}) \;=\; \mathbb{E}\left[\max_{j \in [m]} \lambda_j\right] \;\; .$$

The *expected cost of task i on link j* is

$$c_i^j \;=\; w_i + \sum_{k \neq i} w_k \, p_k^j \;=\; \mathbb{E}\left[\lambda_j\right] + (1 - p_i^j)\, w_i \;\; .$$

A (mixed) strategy profile $\mathbf{P}$ defines a *Nash equilibrium* if and only if any task i will assign non-zero probabilities only to links that minimize c_i^j, that is,

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* Supported in part by the EU within the 6th Framework Programme under contract 001907 (DELIS) and by DFG grant Vo889/1-2.

$(p_i^j) > 0$ implies $c_i^j \leq c_i^q$, for every $q \in [m]$. A Nash equilibrium is called *fully mixed* if $p_i^j > 0$ for all $i \in [n]$, $j \in [m]$. The game under consideration admits a unique fully mixed Nash equilibrium $\mathbf{F}$ in which each job is assigned with probability $\frac{1}{m}$ to each machine [9].

2 The Conjecture

Mavronicolas and Spirakis [9] investigate the social cost of fully mixed Nash equilibria. The motivation for their study is the hope that the techniques for the analysis of fully mixed strategies can be appropriately extended to yield upper bounds on the social cost for general equilibria. This hypothesis is formalized in the following conjecture stated in [4, 5].

Conjecture 1 (FMNE conjecture). The fully mixed Nash equilibrium $\mathbf{F}$ is the worst Nash equilibrium, that is,

$$SC(\mathbf{F}) \ \geq \ SC(\mathbf{P}) \ ,$$

for every Nash equilibrium $\mathbf{P}$.

Several attempts have been made to prove the conjecture. For example, it was shown that the conjecture is true for the case $m = 2$ [5] and for the case that $\mathbf{P}$ refers only to pure equilibria [4]. Furthermore, it was shown that the conjecture holds in an approximate sense if $m = n$ [1, 4]. In [3], an FPRAS for the social cost of the fully mixed Nash equilibrium is presented.

The FMNE conjecture seems to be intuitive and appealing since in case of its validity it would allow for an easy identification of the worst-case mixed Nash equilibrium, whereas the worst case pure Nash equilibrium is NP-hard to compute.

3 The Counterexample

We present a counterexample to the FMNE conjecture. More specifically, we show that there is a family of simple instances of the game for which there exists an equilibrium $\mathbf{P}$ with

$$SC(\mathbf{P}) \ = \ \Omega\left(SC(\mathbf{F}) \cdot \frac{\ln m}{\ln \ln m}\right) \ .$$

Let us remark that this is the worst possible ratio as it follows from the analyses in [2, 8] that the social cost of every Nash equilibrium can be at most $O\left(\frac{\ln m}{\ln \ln m}\right)$ times the optimal social cost.

Theorem 1. *For every m, there exists an instance of the resource allocation game with m machines admitting a Nash equilibrium P with*

$$SC(\mathbf{P}) \ = \ \left(\frac{1}{4} - o(1)\right) \cdot \frac{\ln m}{\ln \ln m} \cdot SC(\mathbf{F}) \ .$$

The instance consist of $n = O(f(m) \cdot m \ln m)$ jobs whose weights differ at most by a factor $O(f(m) \cdot \ln m)$, where f denotes an arbitrary function in $\omega(1)$.

Proof. The counterexample uses only two different kinds of jobs: *Large jobs* of weight 1 and *small jobs* of weight $\frac{1}{k}$, $k \in \mathbb{N}$. Let $\ell \leq m$ denote the number of large jobs. The number of small jobs is $k(m-\ell)$. Thus, the total weight is m and the optimal assignment has social cost 1. We show that the fully mixed equilibrium has social cost close to optimal if the parameters k and ℓ are chosen appropriately.

Lemma 1. *If* $k = \Omega(f(m) \cdot \ln m)$ *and* $\ell = O(\sqrt{n}/f(m))$ *then* $SC(\mathbf{F}) \leq 2 + o(1)$.

Proof. Recall that $\mathbf{F}$ assigns each job with probability $\frac{1}{m}$ to each of the machines.

- The assignment of the large jobs corresponds to a balls-and-bins experiment in which $\ell = O(\sqrt{m}/f(m))$ balls are assigned uniformly at random to m bins. Fact 2 from the Appendix yields that for this experiment the expected number of balls in the fullest bin is $1 + o(1)$. Thus, the expected maximum load due to the large jobs is $1 + o(1)$, too.
- The assignment of the small jobs corresponds to a ball-and-bins experiment in which $k(m-\ell)$ balls are assigned uniformly at random to $m-\ell$ bins for $k = \Omega(f(m) \cdot \ln m)$. Fact 3 shows that for this experiment the expected number of balls in the fullest bin is $(1 + o(1)) \cdot k$. Since each ball corresponds to a job of weight $\frac{1}{k}$, the expected maximum load due to the small jobs is thus $1 + o(1)$ as well.

Combining the upper bounds for the small and the large jobs yieds that the maximum load over all machines is at most $2 + o(1)$ when taking into account all the jobs. □

Next we present a mixed Nash equilibrium whose maximum load is lower-bounded by a function in ℓ.

Lemma 2. *There exists a Nash equilibrium* $\mathbf{P}$ *with* $SC(\mathbf{P}) \geq (1 - o(1)) \cdot \frac{\ln \ell}{\ln \ln \ell}$.

Proof. We construct $\mathbf{P}$ in the following way. The small jobs are assigned using pure strategies. They are distributed evenly among the machines $1, \ldots, m-\ell$ such that each machine receives k small jobs. Hence, their load is fixed to 1. The large jobs are assigned to each of the remaining ℓ machines with probability $1/\ell$. Again, the expected load of these machines is 1. This is a Nash equilibrium since no job can improve by an unilateral move:

- For a small job i assigned to machine j_i, we have $c_i^{j_i} = 1$ and $c_i^j = 1 + 1/k$ for $j \neq j_i$.
- For a large job i, we have $c_i^j = 2 - 1/k$ if $j > m - \ell$ and $c_i^j = 2$ if $j \leq m - \ell$.

The social cost of this equilibrium equals the maximum occupancy of the balls-and-bins experiment where ℓ balls are assigned uniformly at random to ℓ bins. It is well-known that the maximum occupancy of this assignment is $(1 \pm o(1)) \cdot \frac{\ln \ell}{\ln \ln \ell}$ (see, e. g. [6]). □

The ratio between the bounds in Lemma 1 and 2 is maximized by choosing ℓ as large as possible under the constraints specified in Lemma 1. W.l.o.g., let $f(n) = O(\ln n)$. We set $\ell = \Theta(\sqrt{m}/f(m))$. This way, $SC(\mathbf{P}) \geq (\frac{1}{2} - o(1)) \cdot \frac{\ln m}{\ln \ln m}$ and $SC(\mathbf{F}) \leq 2 + o(1)$. This completes the proof of Theorem 1. □

Let us remark that we can fine-tune the above example such that for $m = 14$ machines and $\ell = 3$ large jobs the expected maximum load of $\mathbf{P}$ is $17/9$ and the expected maximum load of $\mathbf{F}$ is $15/9 + 3/14 + \epsilon < 17/9$, where $\epsilon > 0$ can be made arbitrarily small by increasing the number of small jobs. Thus there is a counterexample to the FMNE conjecture with only 14 machines.

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Appendix

The following facts have almost surely been shown somewhere else before.

Fact 2 *Let f denote any function in $\omega(1)$. If $n \le \sqrt{m}/f(m)$ balls are assigned independently and uniformly at random to m bins. Then the expected number of balls in the fullest bin is $1 + o(1)$.*

Proof. The probability that there exists a bin with at least $k \ge 2$ balls is at most

$$m \cdot \binom{n}{k} \left(\frac{1}{m}\right)^k \;\le\; \frac{m^{k/2}}{k! \cdot f(m) \cdot m^{k-1}} \;\le\; \frac{1}{k! \cdot f(m)} \;.$$

Therefore, the expected number of balls in the fullest bin is at most

$$1 + \sum_{k \ge 2} \frac{1}{k! \cdot f(m)} \;=\; 1 + o(1) \;.$$

□

Fact 3 *Let f denote any function in $\omega(1)$. If $n \le m \cdot f(m) \cdot \ln m$ balls are assigned independently and uniformly at random to m bins. Then the expected number of balls in the fullest bin is $f(m) \cdot \ln m + O(\sqrt{f(m)} \cdot \ln m) = (1 + o(1)) \cdot f(m) \cdot \ln m$.*

Proof. Fix any bin. The expected number of balls assigned to that bin is $f(m) \cdot \ln m$. Applying a Chernoff bound (see, e. g. [7]), we obtain that the probability that a bin receives at least $(1+\epsilon) \cdot f(m) \cdot \ln m$ balls is at most

$$\exp\left(-\frac{1}{3}\epsilon^2 \cdot f(m) \cdot \ln m\right) \quad ,$$

for any $\epsilon \in \mathbb{R}$. For $t \geq 0$, let $p(t)$ denote the probability that the maximum occupancy is at least $t \cdot f(m) \cdot \log m$. Applying the union bound and substituting $\epsilon = t - 1$ into the above bound yields

$$p(t) \ \leq \ m \cdot \exp\left(-\frac{1}{3}(t-1)^2 \cdot f(m) \cdot \ln m\right) \quad .$$

The expected maximum occupancy is thus upper-bounded by

$$f(m) \cdot \log m \cdot \int_0^\infty p(t)dt \ \leq \ f(m) \cdot \log m \cdot \left(\tau + \int_\tau^\infty p(t)dt\right) \quad ,$$

where the latter inequality holds for any $\tau \geq 0$. We choose $\tau = 1 + \sqrt{\frac{3}{f(m)}}$ as the term $\int_\tau^\infty p(t)dt$ is sufficiently small for this choice, that is,

$$\begin{aligned}
\int_\tau^\infty p(t)dt &= \int_0^\infty p(\tau + t)dt \\
&\leq \int_0^\infty m \cdot \exp\left(-\frac{1}{3}\left(\sqrt{\frac{3}{f(m)}} + t\right)^2 \cdot f(m) \cdot \ln m\right) dt \\
&\leq \int_0^\infty m \cdot \exp\left(-\frac{1}{3}\left(\frac{3}{f(m)} + 2 \cdot \sqrt{\frac{3}{f(m)}} \cdot t\right) \cdot f(m) \cdot \ln m\right) dt \\
&= \int_0^\infty \exp\left(-\frac{2}{\sqrt{3}} \cdot t \cdot \sqrt{f(m)} \cdot \ln m\right) dt \\
&= \frac{\sqrt{3}}{2 \cdot \sqrt{f(m)} \cdot \ln m} \quad .
\end{aligned}$$

Hence, the expected maximum occupancy is at most

$$\begin{aligned}
f(m) \cdot \log m \cdot &\left(1 + \sqrt{\frac{3}{f(m)}} + \frac{\sqrt{3}}{2 \cdot \sqrt{f(m)} \cdot \ln m}\right) \\
&= f(m) \cdot \log m + O\left(\sqrt{f(m)} \cdot \log m\right) \quad .
\end{aligned}$$

□

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