An Edmonds-Gallai-Type Decomposition for the $j$-Restricted $k$-Matching Problem

Yanjun Li and Jácint Szabó

April 2018
An Edmonds-Gallai-Type Decomposition for the $j$-Restricted $k$-Matching Problem

Yanjun Li* and Jácint Szabó**

Abstract

Given a non-negative integer $j$ and a positive integer $k$, a $j$-restricted $k$-matching in a simple undirected graph is a $k$-matching, so that each of its connected components has at least $j+1$ edges. The maximum non-negative node weighted $j$-restricted $k$-matching problem was recently studied by Li who gave a polynomial-time algorithm and a min-max theorem for $0 \leq j < k$, and also proved the NP-hardness of the problem with unit node weights and $2 \leq k \leq j$. In this paper we derive an Edmonds-Gallai-type decomposition theorem for the $j$-restricted $k$-matching problem with $0 \leq j < k$, using the analogous decomposition for $k$-piece packings given by Janata, Loebl and Szabó, and give an alternative proof to the min-max theorem of Li.

Keywords: Graph Decomposition; Matching; Packing; Transversal Matroid

1 Introduction

In this paper all graphs are simple and undirected. Given a set $\mathcal{F}$ of graphs, an $\mathcal{F}$-packing of a graph $G$ is a subgraph $M$ of $G$ such that each connected component of $M$ is isomorphic to a member of $\mathcal{F}$. An $\mathcal{F}$-packing $M$ is called maximal (resp. maximum) if there is no $\mathcal{F}$-packing $M'$ with $V(M) \subset V(M')$ (resp. $|V(M)| < |V(M')|$). An $\mathcal{F}$-packing $M$ is perfect if $V(M) = V(G)$. The $\mathcal{F}$-packing problem is to find a maximum $\mathcal{F}$-packing of $G$.

Several polynomial $\mathcal{F}$-packing problems are known in the case $K_2 \in \mathcal{F}$. For instance, we get a polynomial packing problem if $\mathcal{F}$ consists of $K_2$ and a finite set of hypomatchable graphs [2, 3, 4, 9]. In all known polynomial $\mathcal{F}$-packing problems with $K_2 \in \mathcal{F}$ it holds that each maximal $\mathcal{F}$-packing is maximum too; those node sets which can be covered by an $\mathcal{F}$-packing form a matroid, and the analogue of

*Krammert School of Management, Purdue University, West Lafayette, IN, USA, li14@purdue.edu
**Google Switzerland, Brandschenkstrasse 110, CH-8802 Zürich, Switzerland, jacintsz@google.com

April 2018
the classical Edmonds–Gallai decomposition theorem for matchings (see \[6, 7, 5, 16\]) holds.

The first polynomial $\mathcal{F}$-packing problem with $K_2 \notin \mathcal{F}$ was considered by Kaneko \[11\], who presented a Tutte-type characterization of graphs having a perfect packing by long paths, that is, by paths of length at least 2.

A shorter proof for Kaneko’s theorem and a min-max formula was subsequently found by Kano, Katona and Király \[12\] but polynomiality remained open. The long path packing problem was generalized by Hartvigsen, Hell and Szabó \[8\] by introducing the $k$-piece packing problem, that is, the $\mathcal{F}$-packing problem where $\mathcal{F}$ consists of all connected graphs with highest degree exactly $k$. Such a graph is called a $k$-piece. Note that a 1-piece is just $K_2$, thus the 1-piece packing problem is the classical matching problem. The 2-piece packing problem is equivalent to the long path packing problem because a 2-piece is either a long path or a circuit $C$ of length at least 3 so deleting an edge from $C$ results in a long path. The main result of \[8\] is a polynomial algorithm for finding a maximum $k$-piece packing. Later, Janata, Loebl and Szabó \[10\] gave a canonical Edmonds–Gallai-type decomposition for the $k$-piece packing problem, showed that maximal and maximum packings do not coincide, and actually the maximal packings have a nicer structure than the maximum ones.

As another generalization of matchings, Li \[14\] introduced $j$-restricted $k$-matchings. For an integer $k > 0$, a $k$-matching of $G$ is a subgraph $M$ of $G$ with no isolated node and degrees at most $k$. For two integers $j \geq 0$ and $k > 0$, a $j$-restricted $k$-matching of $G$ is a $k$-matching whose each connected component has more than $j$ edges \[14\]. Obviously, $k$-matchings are equal to 0-restricted $k$-matchings. Moreover, the $(k - 1)$-restricted $k$-matching problem is exactly the maximum matching problem for $k = 1$ and the long path packing problem for $k = 2$.

Given non-negative weights on the nodes of $G$, the maximum non-negative node weighted $j$-restricted $k$-matching problem is to find a $j$-restricted $k$-matching of $G$ such that the total weight of the nodes covered is maximized. Note that, contrary to the usual analysis of $k$-matchings, here we are interested in the maximum number of covered nodes, not edges. In \[14\], a polynomial-time algorithm composed of a min-cost max-flow algorithm and an alternating tree algorithm was proposed for solving the above problem with $0 \leq j < k$, and the algorithm was proved valid by showing a min-max theorem (Theorem 2.5 in this paper). In contrast, the maximum unit node weight $j$-restricted $k$-matching problem with $2 \leq k \leq j$ is proved to be NP-hard in \[14\].

There is a simple but essential relation between $k$-piece packings and $j$-restricted $k$-matchings, namely that every $k$-piece is a $j$-restricted $k$-matching for every $0 \leq j < k$. This connection has many important implications. The most prominent example is the fact that the critical graphs with respect to the $j$-restricted $k$-matching problem are also critical with respect to the $k$-piece packing problem (the role of critical graphs will be clear from the Edmonds–Gallai-type decomposition Theorems 2.3 and 3.4). This connection makes it possible to translate the analysis on $k$-piece packings to $j$-restricted $k$-matchings, and to prove analogous results.

Exploiting this relationship, in this paper we give an alternative proof to Theorem

\[ EGRES \text{ Technical Report No.} \ 2018-05 \]
In addition, we prove two new results on the \(j\)-restricted \(k\)-matching problem. Theorem 2.3 is an Edmonds-Gallai-type decomposition, and Theorem 2.4 is a characterization of the maximal \(j\)-restricted \(k\)-matchings. Both proofs are based on the analogous results on \(k\)-piece packings [10].

After formulating the main results and the min-max Theorem 2.5 of Li [14] in Section 2, we review the \(k\)-piece packing problem and associated concepts and results from [8, 10] in Section 3. From these results we then derive Theorem 2.3 in Section 4, and Theorem 2.4 in Section 5. In Section 5 we give the alternative proof to Theorem 2.5, as well. Finally, we conclude the paper with open questions in Section 6.

## 2 Main results

We need some notations to state our main results, Theorems 2.3 and 2.4. For a simple, undirected graph \(G\) we denote by \(c(G)\) the number of connected components of \(G\), and by \(\Delta(G)\) the largest degree of \(G\). For \(X \subseteq V(G)\), let \(G[X]\) denote the subgraph induced by \(X\); let \(\Gamma(X)\) denote the set of nodes not belonging to \(X\) but adjacent to a node in \(X\); and let \(G \setminus X\) denote the subgraph of \(G\) induced by the nodes of \(G\) not in \(X\). An edge is said to enter \(X\) if exactly one end node of the edge is contained in \(X\). A node set \(X \subseteq V(G)\) is said to be covered (resp. missed) by a subgraph \(M\) of \(G\) if \(X \subseteq V(M)\) (resp. \(X \cap V(M) = \emptyset\)).

**Definition 2.1.** A connected graph \(G\) is hypomatchable if \(G \setminus \{v\}\) has a perfect matching for every \(v \in V(G)\).

**Definition 2.2.** For an integer \(k \geq 1\) a connected graph \(G\) is a \(k\)-blossom if there exists a hypomatchable graph \(F\) with \(|V(F)| \geq 3\), such that \(V(G) = V(F) \cup \{v_1, \ldots, v_{k-1} : v \in V(F)\}\) and \(E(G) = E(F) \cup \{vv_1, \ldots, vv_{k-1} : v \in V(F)\}\).

A connected graph \(G\) is a \(sub-j\)-graph if \(|E(G)| \leq j\).

For a \(k\)-blossom \(G\), where \(k \geq 2\), every degree-1 node of \(G\) is called a tip; every node of a 1-blossom is called a tip; and every \(sub-j\)-graph itself is called a \(tip\). See Figure 1 for some examples of \(k\)-blossoms and \(sub-j\)-graphs. Every tip is circled.

One of our main results is the following.

**Theorem 2.3.** [Edmonds-Gallai decomposition for \(j\)-restricted \(k\)-matchings] For a graph \(G\) and integers \(0 \leq j < k\), let

\[
U(G) = \{v \in V(G) : v \text{ is missed by a maximal } j\text{-restricted } k\text{-matching of } G\},
\]

\[
D = \{v : |U(G \setminus \{v\})| < |U(G)|\}, \ A = \Gamma(D) \text{ and } C = V(G) \setminus (D \cup A). \ Then
\]

1. every connected component of \(G[D]\) is either a \(k\)-blossom or a \(sub-j\)-graph,

2. for all \(\emptyset \neq A' \subseteq A\), the number of the components of \(G[D]\) that are adjacent to \(A'\) is at least \(k|A'| + 1\),

3. \(G[C]\) has a perfect \(j\)-restricted \(k\)-matching, and

\[ EGRES Technical Report No. 2018-05 \]
Section 2. Main results

Figure 1: $k$-blossoms and sub-$j$-graphs. Tips are circled.

4. A $j$-restricted $k$-matching $M$ of $G$ is maximal if and only if

(a) exactly $k|A|$ connected components of $G[D]$ are entered by an edge of $M$ and these connected components are completely covered by $M$,

(b) for every connected component $H$ of $G[D]$ not entered by $M$, $M[H]$ is a maximal $j$-restricted $k$-matching of $H$, and

(c) $M[C]$ is a perfect $j$-restricted $k$-matching of $G[C]$.

This is a generalization of the classical Edmonds-Gallai decomposition for matchings \([6, 7, 5]\). We will prove Theorem 2.3 in Section 4 by deriving it from the Edmonds-Gallai decomposition for $k$-piece packings (Theorem 3.4, proved in \([10]\)).

It is a well known fact in matching theory that those node sets which can be covered by a matching form a matroid. In the $j$-restricted $k$-matching problem, maximal and maximum $j$-restricted $k$-matchings do not coincide, shown by the 5-node tree with maximum degree 3 for $j = 1, k = 2$ (this is generally true for any $k \geq 2$). This is the reason that in the $j$-restricted $k$-matching problem the above matroidal property holds only in the following weaker form.

**Theorem 2.4.** There exists a partition $\pi$ on $V(G)$ and a matroid $P$ on $\pi$ such that the node sets of the maximal $j$-restricted $k$-matchings are exactly the node sets of the form $\bigcup\{X : X \in \pi'\}$ where $\pi' \subseteq \pi$ is a base of $P$.

The analogue of Theorem 2.4 for $k$-piece packings was proved in \([10]\).

A Berge-type characterization 2.5 of $j$-restricted $k$-matchings with maximum node weight was proved by Li \([14]\), based on a polynomial time alternating tree algorithm. In this paper we will derive it by analyzing the maximum weight bases of the matroid $P$ above. Assume that a non-negative weight function $w : V(G) \to \mathbb{R}_+$ is given. \([14]\) defines the **deficiency weight** of a $(j, k)$-galaxy $G$ as

1. $w(G) = \sum\{w(v) : v \in V(G)\}$ if $G$ is a sub-$j$-graph,
Section 3. $k$-piece packings

2. $w(G) = \min\{w(v) : v \text{ is a tip of } G\}$ if $G$ is a $k$-blossom.

Let $(j,k)$-gal$_i(G)$ denote the number of $k$-blossom and sub-$j$-graph components $H$ of a graph $G$ with $w(H) \geq t$. (The rationale of this notation will be clear later.)

Theorem 2.5. \[14\] [Weighted $j$-restricted $k$-matchings] Let $G$ be a graph of size $n$, and $w : V(G) \to \mathbb{R}_+$ non-negative node weights. Then the maximum total weight of a $j$-restricted $k$-matching of $G$ is

$$\sum \{w(v) : v \in V(G)\} - \max_{i=1}^{n} (t_i - t_{i-1}) \left( (j,k)\text{-gal}_i(G \setminus A_i) - k|A_i| \right),$$

where the max is taken over all sequences of node sets $V(G) \supseteq A_1 \supseteq A_2 \supseteq \cdots \supseteq A_n$ and $0 = t_0 \leq t_1 \leq \ldots \leq t_n$.

The analogue of Theorem 2.5 for $k$-piece packings was proved in [8]. We will prove Theorems 2.4 and 2.5 in Section 5 by analyzing the matroid $\mathcal{P}$ in Theorem 2.4.

3 $k$-piece packings

In this section we collect the relevant notions and results on $k$-piece packings from [8, 10]. In the rest of the paper $k$ is a fixed positive integer.

A $k$-piece is a connected graph $G$ with $\Delta(G) = k$. The $k$-piece packing problem is, given a graph $G$, to find a maximum $k$-piece packing of $G$. The main result of [8] is a polynomial-time algorithm for the $k$-piece packing problem. Moreover, from the algorithm, the graphs with a perfect $k$-piece packing were characterized, and a min-max theorem for the size of a maximum $k$-piece packing was derived.

It was revealed in [8] that $k$-galaxies play a critical role in solving the $k$-piece packing problem.

Definition 3.1. For a graph $G$ we denote $I_G = G[\{v \in V(G) : \deg_G(v) \geq k\}]$.

Definition 3.2. For an integer $k \geq 1$ the connected graph $G$ is a $k$-galaxy if it satisfies the following properties:

- each connected component of $I_G$ is a hypomatchable graph, and
- for each $v \in V(I_G)$, there are exactly $k - 1$ edges between $v$ and $V(G) \setminus V(I_G)$, each being a cut edge of $G$.

For a $k$-galaxy $G$, where $k \geq 2$, every connected component of $G \setminus V(I_G)$ is called a tip, and every node of a 1-galaxy is called a tip. In the case $k \geq 2$ a $k$-galaxy may consist of only a single tip (a graph with highest degree at most $k - 1$), but must always contain at least one tip.

A hypomatchable graph has no node of degree 1 so a $k$-galaxy has no node of degree $k$. Furthermore, each connected component of $I_G$ is a hypomatchable graph on at least 3 nodes. Galaxies generalize hypomatchable graphs because the 1-galaxies...
Figure 2: Galaxies

are exactly the hypomatchable graphs. Kaneko introduced the 2-galaxies under the name ‘sun’ [11]. See Figure 3 for some $k$-galaxies. The nodes of $I_G$ are drawn as big dots, the edges of $I_G$ as thick lines, and every tip is circled except in the 4-galaxy where not all are circled.

Obviously, every $k$-piece is a $j$-restricted $k$-matching. This is the reason that the critical graphs for the $j$-restricted $k$-matching problem can be directly derived from $k$-galaxies, as we will see in Theorem 4.3.

We will use the following fact at many places.

Lemma 3.3. [8] A $k$-galaxy has no perfect $k$-piece packing.

The following Edmonds-Gallai-type decomposition for the $k$-piece packings was proved in [10]. The classical Edmonds-Gallai-theorem [5, 6, 7] first defines the node set $D$ to consist of those nodes which can be missed by a maximal (or equivalently, maximum) matching. In the $k$-piece packing problem, we need a different formulation, and so Theorem 3.4 is not a direct generalization of the classical Edmonds-Gallai-theorem.

Theorem 3.4. [Edmonds-Gallai decomposition for $k$-piece packings] For a graph $G$, let $U^k(G) = \{v \in V(G) : v$ is missed by a maximal $k$-piece packing of $G\}$, $D^k = \{v \in V(G) : |U^k(G \setminus \{v\})| < |U^k(G)|\}$, $A^k = \Gamma(D^k)$ and $C^k = V(G) \setminus (D^k \cup A^k)$. Then

1. every connected component of $G[D^k]$ is a $k$-galaxy,
2. for all $\emptyset \neq A' \subseteq A^k$, the number of the components of $G[D^k]$ that are adjacent to $A'$ is at least $k|A'| + 1$, and
3. $G[C^k]$ has a perfect $k$-piece packing.

In the graph packing terminologies, the node set $A^k$ in the above theorem is called a barrier, and the $k$-galaxies are called critical graphs in the $k$-piece packing problem.

4 Proof of Theorem 2.3

In this section we make use of the established connection between $j$-restricted $k$-matchings and $k$-piece packings to derive Theorem 2.3 from Theorem 3.4.
4.1 \((j,k)\)-galaxies and \(k\)-solar systems

In this subsection we define \((j,k)\)-galaxies, introduce \(k\)-solar-systems, make observations on both of them, and review the rank of the transversal matroid of bipartite graphs.

**Definition 4.1.** For integers \(0 \leq j < k\), a connected graph is a \((j,k)\)-\emph{galaxy} if it is a \(k\)-galaxy without a perfect \(j\)-restricted \(k\)-matching.

**Lemma 4.2.** If \(k \geq 2\), \(j = k - 1\) and \(M\) is a \(j\)-restricted \(k\)-matching of a \(k\)-blossom \(G\), then there exists a tip \(T\) of \(G\) such that \(V(T) \cap V(M) = \emptyset\).

\begin{proof}
\text{Let} \(G\) \text{denote the set of nodes in the tips of } G. \text{Suppose that every node in } T_G \text{ is covered by } M. \text{Then also all edges in } E' = \{uv : u \in T_G, v \in V(I_G)\} \text{ are contained in } M \text{ because } j \geq 1. \text{Note that every node } v \in V(I_G) \text{ has } k - 1 \text{ incident edges in } E'. \text{Let } M' = M[V(I_G)]. \text{Now } \deg_{M'}(v) \geq 1 \text{ for all } v \in V(I_G), \text{as otherwise the connected component of } M \text{ containing } v \text{ would only have } k - 1 \text{ edges, which is not a } (k-1)\text{-restricted } k\text{-matching. On the other hand, } \Delta(M') \leq 1 \text{ as otherwise } \Delta(M) > k \text{ would hold. Thus } M' \text{ is a perfect matching of the hypomatchable graph } I_G, \text{which is impossible. As every tip consists of only one node, the statement follows.} \qedhere
\end{proof}

The next theorem shows the connection between \(k\)-galaxies, \(k\)-blossoms and sub-\(j\)-graphs.

**Theorem 4.3.** For \(j < k - 1\), the \((j,k)\)-galaxies are the sub-\(j\)-graphs. For \(j = k - 1\), the \((j,k)\)-galaxies are the \(k\)-blossoms and the sub-\(j\)-graphs.

\begin{proof}
First, \(k\)-blossoms and sub-\(j\)-graphs are clearly \(k\)-galaxies. Now we prove that they have no \(j\)-restricted \(k\)-matchings, and thus \((j,k)\)-galaxies for the given \(j,k\)'s. Trivially, this holds for sub-\(j\)-graphs for all \(0 \leq j < k\). As for \(k\)-blossoms in the case \(j = k - 1\), for \(k = 1\) observe that both \((0,1)\)-galaxies and \(1\)-blossoms are just hypomatchable graphs, and for \(k \geq 2\) use Lemma 4.2.

Now we prove that every \((j,k)\)-galaxy is either a \(k\)-blossom or a sub-\(j\)-graph for the given \(j,k\)'s.

Let \(G\) be a \((j,k)\)-galaxy. If \(I_G = \emptyset\), that is \(\Delta(G) < k\), then it is clear that \(G\) has no perfect \(j\)-restricted \(k\)-matching if and only if it is a sub-\(j\)-graph. So assume that \(I_G \neq \emptyset\).

For the case of \(j < k - 1\), let \(G' = (V(G), E(G) \setminus E(I_G))\) be the subgraph of \(G\) without the edges of \(I_G\). Clearly, \(\Delta(G') = k - 1\). Moreover, every connected component of \(G'\) has at least \(k - 1 > j\) edges because it contains a node from \(V(I_G)\). Thus \(G'\) is a perfect \(j\)-restricted \(k\)-matching of \(G\) and so \(G\) cannot be a \((j,k)\)-galaxy.

Let us consider the case of \(j = k - 1\). As we already observed, in the case of \(k = 1\), both \((0,1)\)-galaxies and \(1\)-blossoms are just hypomatchable graphs, so let us assume that \(k \geq 2\).

If \(I_G\) is connected, then we prove that every tip of \(G\) consists of a single node, and thus \(G\) is a \(k\)-blossom. Otherwise, suppose that some \(v \in V(I_G)\) is connected to a tip of two or more nodes. Since \(I_G\) is hypomatchable, we let \(N'\) be a matching of \(I_G\).
that covers all nodes of $I_G$ but $v$. Then the subgraph of $G$ consisting of all edges of $G$ except for $E(G) \setminus E(N')$ is a perfect $j$-restricted $k$-matching of $G$, a contradiction to the definition of a $(j,k)$-galaxy.

If $I_G$ has at least two connected components, we let $T$ be a tip of $G$ that is connected to at least two components of $I_G$. For every component $C$ of $I_G$, let $v_C$ be the unique node of $C$ that is closest to $T$ in $G$, and let $N_C$ be a perfect matching of $C \setminus \{v_C\}$. Let $E' = \bigcup\{E(N_C) : C$ is a connected component of $I_G\}$, and let $M$ be the subgraph of $G$ consisting of all edges of $G$ except $E(I_G) \setminus E'$. We prove that $M$ is a perfect $j$-restricted $k$-matching of $G$. As $M \cap E(I_G)$ has maximum degree $1$, $\Delta(M) \leq k$, so it is enough to prove that $|E(C_M)| \geq k$ for every connected component $C_M$ of $M$.

1. The component $C_M$ containing $T$ necessarily covers two nodes $u, v \in V(I_G)$ from two different components of $I_G$, thus $C_M$ has at least $2(k - 1) \geq k$ edges.

2. All other components $C_M$ contain an edge $uv \in E'$ and the nodes $u, v$ together are incident to $2(k - 1) + 1 > k$ edges of $C_M$.

The maximal matchings of a hypomatchable graph $G$ are exactly the perfect matchings of $G \setminus \{v\}$ for the nodes $v \in V(G)$. The characterization of the maximal $j$-restricted $k$-matchings of a $(j,k)$-galaxy can be stated by means of the tips in Corollary

\[ \text{Corollary 4.4. If } M \text{ is a } j\text{-restricted } k\text{-matching of a } (j,k)\text{-galaxy } G, \text{ then there exists a tip } T \text{ of } G \text{ such that } V(M) \cap V(T) = \emptyset. \]

\[ \text{Proof. If } G \text{ is a sub-} j\text{-graph, then } M \text{ must be empty otherwise it would have a connected component with at most } j \text{ edges. For } k\text{-blossoms, use the definition of hypomatchable graphs for } k = 1 \text{ and apply Lemma 4.2 for } k \geq 2. \]

\[ \text{Lemma 4.5. If } T \text{ is a tip of a } (j,k)\text{-galaxy } G, \text{ then } G \setminus V(T) \text{ has a perfect } j\text{-restricted } k\text{-matching.} \]

\[ \text{Proof. In Lemma 3.5 of [10], the analogous result for } k\text{-galaxies and } k\text{-piece packings is proved. As } G \text{ is also a } k\text{-galaxy, this implies that } G \setminus V(T) \text{ has a perfect } k\text{-piece packing, which is itself a perfect } j\text{-restricted } k\text{-matching.} \]

We note that Lemma 4.5 is also easy to prove directly.

\[ \text{Corollary 4.6. The maximal } j\text{-restricted } k\text{-matchings of a } (j,k)\text{-galaxy } G \text{ are exactly the perfect } j\text{-restricted } k\text{-matchings of } G \setminus V(T), \text{ where } T \text{ is a tip of } G. \]

\[ \text{Proof. By Corollary 4.4 and Lemma 4.5.} \]

\[ \text{Definition 4.7. [10] A connected graph } G \text{ is a } k\text{-solar-system (see Figure 4.1) if it has a node } y, \text{ called center, such that } \deg_G(y) = k \text{ and } G \setminus \{y\} \text{ has } k \text{ connected components, each being a } (j,k)\text{-galaxy.} \]
Lemma 4.8. Every $k$-solar-system has a perfect $j$-restricted $k$-matching.

Proof. In Lemma 3.10 of [10], it is proved that a $k$-solar system has a perfect $k$-piece packing. This is itself a perfect $j$-restricted $k$-matching. \qed

Lemma 4.8 is also easy to prove directly.

4.2 Tools from matroid theory

We will make use of transversal matroids of bipartite graphs. In this subsection we list the relevant results which we will use in later proofs. Let $G$ be a graph and $A, D \subseteq V(G)$ disjoint node sets. Let $kA = \{v_1, \ldots, v_k : v \in A\}$ and denote the set of connected components of $G[D]$ by $D$. We denote by $K_{A,D}$ the bipartite graph $(kA, D, \{v_iH : 1 \leq i \leq k, H \in D \text{ is connected to node } v \in A\})$.

Definition 4.9. $A$ is $k$-matched into $D$ by $N$ if $N$ is a matching of $K_{A,D}$ such that $\deg_N(v_i) = 1$ for all $v \in A, 1 \leq i \leq k$. $A$ has $k$-surplus in $K_{A,D}$ if for every component $H \in D, A$ can be $k$-matched into $D \setminus V(H)$.

Remark 4.10. By König’s theorem [13], $A$ has $k$-surplus in $K_{A,D}$ if and only if for every $\emptyset \neq A' \subseteq A, A'$ is connected to at least $k|A'| + 1$ connected components of $G[D]$.

The transversal matroid $T_K$ of a bipartite graph $K = (U, V; E)$ is a matroid on $V$ where a set $V' \subseteq V$ is independent if it can be covered by a matching of $K$. In a matroid, an element is a bridge if it is contained in every base.

Theorem 4.11. [17] The rank of $T_K$ is $|V \setminus X| + \Gamma_K(X)$, where $X$ is the set of the non-bridge elements of $T_K$.

For $A \subseteq V(G)$, let $D_A(G) = \bigcup\{V(H) : H \text{ is a } (j,k)\text{-galaxy component of } G \setminus A\}$, and let $C_A(G) = V(G) \setminus (D_A \cup A)$. We sometimes use the notation $D_A$ and $C_A$, respectively.

Definition 4.12. $A$ has $k$-surplus if it has $k$-surplus in $K_{A,D_A}$. $A$ is perfect if $G[C_A]$ has a perfect $j$-restricted $k$-matching.
4.3 The structure of maximal $j$-restricted $k$-matchings

Now we turn to establishing the canonical Edmonds-Gallai-type decomposition Theorem 2.3 for $j$-restricted $k$-matchings.

**Theorem 4.13.** There exists a perfect node set $A \subseteq V(G)$ with $k$-surplus.

*Proof.* Let us consider the decomposition $V(G) = D^k \cup A^k \cup C^k$ of Theorem 3.4. In this decomposition the connected components of $G[D^k]$ are $k$-galaxies, $G[C^k]$ has a perfect $k$-piece packing, and by Remark 4.10, $A^k$ has $k$-surplus in $K_{A^k,D^k}$. Figure 4.3 is an illustration of this proof.

Let $H^k = \{H : H \text{ is a connected component of } G[D^k]\}$, $H' = \{H \in H^k : H \text{ is a } (j,k)\text{-galaxy}\}$, and $D' = \bigcup\{V(H) : H \in H'\}$. Let $T^k$ be the transversal matroid on $H^k$ in the bipartite graph $K_{A^k,D^k}$, and $T' = T^k|H'$. Applying Theorem 4.11 to $T'$ we get that $r_{T'} = |H' \setminus D| + k|A|$, where $D$ consists of the non-bridge elements of $T'$, $D = \bigcup\{V(H) : H \in D\}$, and $A = \Gamma_G(D)$. Define $M = T'|D$. That $M$ has no bridge means that every element $H \in D$ is missed by some base of $M$, that is, $A$ can be $k$-matched into $D \setminus \{H\}$. Thus $A$ has $k$-surplus in $K_{A,D}$.

We prove that $A$ is perfect. By Theorem 3.4 $G[C^k]$ has a perfect $k$-piece packing, so it also has a perfect $j$-restricted $k$-matching $M_1$. We show that $G[(A^k \setminus A) \cup (D^k \setminus D)]$ has a perfect $j$-restricted $k$-matching, too. Take a base $B$ of $T'|D$, extend it to a base $B^k$ of $T^k$, and take the matching $N^k$ in $K_{A^k,D^k}$ defining $B^k$. Recall that $|B| = k|A|$ and $|B^k| = k|A^k|$, thus $N^k$ matches $kA$ to $B$ in $K_{A,D}$ and $k(A^k \setminus A)$ to $B^k \setminus B$ in $K_{A^k,D^k}$.

Using Lemma 4.8, $N^k$ gives rise to a perfect $j$-restricted $k$-matching $M_2$ in the subgraph induced by

$$\{A^k \setminus A\} \cup \{V(H) : H \in H^k \setminus D \text{ is covered by } N^k\}.$$ 

As the components in $H' \setminus D$ are bridges in $T'$, all these components are covered by $N^k$. Now consider a component $H \in H^k \setminus H'$ not covered by $N^k$. By definition, $H$ has a perfect $j$-restricted $k$-matching $M_H$. Thus $M_1 \cup M_2 \cup \bigcup\{M_H : H \in H^k \setminus H' \text{ not covered by } N^k\}$ is a perfect $j$-restricted $k$-matching of $V(G) \setminus (A \cup D)$. As the components in $D$ are $(j,k)$-galaxies, $C_A = V(G) \setminus (A \cup D)$, and so $A$ is perfect. Moreover, $D_A = D$, and so $A$ has surplus. \hfill \Box

**Definition 4.14.** Let $A_G = A$ as defined in the proof of Theorem 4.13, $D_G = D_A$ and $C_G = C_A$. The decomposition $V(G) = D_G \cup A_G \cup C_G$ is called the canonical decomposition of $G$ for $j$-restricted $k$-matchings.

Now we investigate the structure of maximal $j$-restricted $k$-matchings of $G$.

**Definition 4.15.** For $A \subseteq V(G)$, let $W_A(G)$ or simply $W_A = \bigcup\{T_H : T_H \text{ is the node set of a tip of a } (j,k)\text{-galaxy component } H \text{ of } G[D_A]\}$.

Recall the definition of $U(G)$ in Theorem 2.3.

EGRES Technical Report No. 2018-05
4.3 The structure of maximal $j$-restricted $k$-matchings

Figure 4: Creating the canonical decomposition for $j$-restricted $k$-matchings from the decomposition for $k$-piece packings ($k = 2$)

Lemma 4.16. Let $A \subseteq V(G)$ be perfect and $k$-matchable into $D_A$. Then a subgraph $M$ of $G$ is a maximal $j$-restricted $k$-matching of $G$ if and only if

1. exactly $k|A|$ connected components of $G[D_A]$ are entered by $M$ and these components are completely covered by $M$,
2. if $H$ is a connected component of $G[D_A]$ not entered by $M$, then there exists a tip $T$ of $H$ such that $M[H]$ is a perfect $j$-restricted $k$-matching of $H \setminus V(T)$, and
3. $M[C_A]$ is a perfect $j$-restricted $k$-matching of $G[C_A]$.

It holds that $U(G) \subseteq W_A$. Moreover, if $A$ has surplus then $U(G) = W_A$.

Proof. Assume that $M$ is a $j$-restricted $k$-matching satisfying the properties 1, 2 and 3, and $M'$ is a $j$-restricted $k$-matching with $V(M) \subseteq V(M')$. By Lemma 4.4, $M'$ must enter more than $k|A|$ connected components of $G[D_A]$, which is not possible. Thus $M$ is maximal.

Now let $M$ be a maximal $j$-restricted $k$-matching of $G$. We construct a $j$-restricted $k$-matching $M'$ for which $V(M) \subseteq V(M')$ holds, and if $M$ fails any of the properties 1, 2 and 3, then even $V(M) \subseteq V(M')$. This is clearly enough to prove.

Let $\mathcal{H} = \{H : H$ is a connected component of $G[D_A]\}$, and let $\mathcal{T}$ be the transversal matroid on $\mathcal{H}$ in the bipartite graph $K_{A,D_A}$. Let $\mathcal{H}_M = \{H \in \mathcal{H} : H$ is entered by $M\}$, and take a base $\mathcal{B} \supseteq \mathcal{H}_M$ of $\mathcal{T}$. $A$ can be $k$-matched into $D_A$, so $r_T = k|A|$ and thus $|\mathcal{B}| = k|A|$. By Lemma 4.4 one can choose a tip $T_H$ missed by $M$ in each component $H \in \mathcal{H} \setminus \mathcal{B}$. Similarly as in the proof of Theorem 4.13, we construct a $j$-restricted $k$-matching $M'$ of $G$ missing exactly these tips. First, take a matching $N$ in $K_{A,D_A}$ that defines the base $\mathcal{B}$. In a component $H \in \mathcal{H} \setminus \mathcal{B}$, take a perfect $j$-restricted $k$-matching...
Lemma 4.17. If $N$ gives rise to a perfect $j$-restricted $k$-matching $M_2$ in the subgraph induced by

$$A \cup \bigcup \{V(H) : H \in \mathcal{B}\}.$$ 

Finally, take a perfect $j$-restricted $k$-matching $M_3$ of $G[C_A]$. Now $M' = M_1 \cup M_2 \cup M_3$

is a $j$-restricted $k$-matching with $V(M') = V(G) \setminus \bigcup \{V(H) : H \in \mathcal{H} \setminus \mathcal{B}\} \supseteq V(M)$. Trivially, $|\mathcal{H}_M| \leq k|A|$. In fact, $|\mathcal{H}_M| = k|A|$ holds because otherwise the matching $N$ would enter strictly more connected components of $G[D_A]$ than $M$, resulting in $V(M) \subsetneq V(M')$, a contradiction. The properties 1 and 2 are straightforward by the maximality of $M$ and by Corollary 4.6. For the property 3, observe that $M$ has no edge joining $A$ to $C_A$ because otherwise $|\mathcal{H}_M| < k|A|$ would hold.

It clearly follows that $U(G) \subseteq W_A$. We show that $U(G) = W_A$ if $A$ has surplus. Let $T$ be an arbitrary tip in a $(j, k)$-galaxy component $H_0$ of $G[D_A]$. $A$ has surplus, so $T$ has a base $\mathcal{B} \subseteq \mathcal{H} \setminus H_0$. Now choose a tip $T_H$ in each component $H \in \mathcal{H} \setminus (H_0 \cup \mathcal{B})$. Similarly as above, one can construct a maximal $j$-restricted $k$-matching $M$ of $G$ missing exactly these tips, including $T$.

4.4 Uniqueness of the canonical decomposition

In the matching case, that is, when $k = 1$, it holds that $W_A = D_A$, thus Lemma 4.16 itself characterizes $D_A$ in the canonical decomposition. In the general case, only $W_A \subseteq D_A$ holds, so we have to go one step further in order to characterize $D_A$ in Theorem 4.18. First we need the following lemma.

**Lemma 4.17.** If $G$ is a $(j, k)$-galaxy and $v \in V(G)$, then every connected component of $G \setminus \{v\}$ is either a $(j, k)$-galaxy or has a perfect $j$-restricted $k$-matching. Moreover, with

$$W^v = \{u : u \text{ is in a tip in a } (j, k)\text{-galaxy component } H \text{ of } G \setminus \{v\}\}$$

and $W_G = \{u : u \text{ is in a tip of } G\}$, we have $W^v \subseteq W_G$.

**Proof.** If $G$ is a sub-$j$-graph, then all connected components of $G \setminus \{v\}$ are sub-$j$-graphs and thus are $(j, k)$-galaxies. Moreover, $W^v = V(G) \setminus \{v\} \subseteq V(G) = W_G$.

Let $j = k - 1$ and $G$ be a $k$-blossom. For $k = 1$, the statement follows from the definition of hypomatchable graphs. For $k \geq 2$, there are two cases to consider:

1. $v$ is a tip. Let $u \in V(I_G)$ be the neighbor of $v$, and $x \in V(I_G)$ some neighbor of $u$. Take a perfect matching $N$ of $I_G \setminus \{x\}$, and let $N' = N \cup \{ux\}$. Clearly, $\deg_N(y) = 1$ for all $y \in V(I_G) \setminus \{u\}$ and $\deg_{N'}(u) = 2$. Now consider the graph $J = (V(G), (E(G) \setminus E(I_G)) \cup E(N')) \setminus \{v\}$. Now every connected component of $J$ has maximum degree $k$, so it is a $j$-restricted $k$-matching of $G \setminus \{v\}$. Clearly, $W^v = \emptyset \subsetneq W_G$.  

EGRES Technical Report No. 2018-05
2. \( v \in V(I_G) \). Denote by \( W' \) the tips connected to \( v \) in \( G \). In \( G \setminus \{v\} \), the tips in \( W' \) become singletons, and thus \((j,k)\)-galaxies. Now take a perfect matching \( N \) of \( I_G \setminus \{v\} \). Consider the graph \( J = (V(G) \setminus E(I_G)) \cup \{v\} \setminus W' \). Now every connected component of \( J \) has maximum degree \( k \), so it is a \( j \)-restricted \( k \)-matching of \( G \setminus \{v\} \). It follows that \( W' \subseteq W_G \).

\[ \square \]

The uniqueness of the canonical decomposition will follow from the next theorem.

**Theorem 4.18.** Every graph \( G \) has a unique perfect node set \( A \subseteq V(G) \) with \( k \)-surplus. For this node set \( A \), it holds that

\[
D_A = \{ v : U(G \setminus \{v\}) \not\subseteq U(G) \} \cup \{ v : |U(G \setminus \{v\})| < |U(G)| \}.
\]

**Proof.** Let \( A \subseteq V(G) \) be perfect with \( k \)-surplus. By Lemma 4.16, we know that \( U(G) = W_A \). Now we investigate the canonical decomposition of \( G \setminus \{v\} \) for a node \( v \in V(G) \) in the following three cases:

1. \( v \in C_A \). Denote the graph \( G[C_A \setminus \{v\}] \) by \( G' \). Observe that in \( G \setminus \{v\} \) the set \( A'' = A \cup A_{G'} \) is perfect with \( k \)-surplus. Thus by Lemma 4.16, \( U(G \setminus \{v\}) = W_{A''} \supseteq W_A = U(G) \).

2. \( v \in A \). In the graph \( G \setminus \{v\} \) the set \( A \setminus \{v\} \) is perfect with \( k \)-surplus, so by Lemma 4.16, \( U(G \setminus \{v\}) = W_{A \setminus \{v\}} = W_A = U(G) \).

3. \( v \in V(H) \) for a \((j,k)\)-galaxy component \( H \) of \( G[D_A] \). By Lemma 4.17, \( \emptyset \) is perfect and has \( k \)-surplus in the graph \( H \setminus \{v\} \). Let \( D' = \{V(K) : K \text{ is a } (j,k)\text{-galaxy component of } H \setminus \{v\}\} \) and \( C' = \{V(K) : K \text{ is a component of } H \setminus \{v\} \text{ with a perfect } j\text{-restricted } k\text{-matching}\} \). Furthermore, let \( D'' = (D_A \setminus V(H)) \cup D' \) and \( C'' = C_A \cup C' \). Lemma 4.17 implies that \( W_A(G \setminus \{v\}) \subseteq W_A(G) \). In the graph \( G \setminus \{v\} \), the set \( A \) is perfect because \( G[C''] \) has a perfect \( j\)-restricted \( k \)-matching. Moreover, \( A \) can be \( k \)-matched into \( D'' \) in \( G \setminus \{v\} \) because \( A \) has \( k \)-surplus in \( G \). So by Lemma 4.16, we have \( U(G \setminus \{v\}) \subseteq W_A(G \setminus \{v\}) \subseteq W_A(G) = U(G) \).

We have proved that, if \( A \subseteq V(G) \) is perfect with \( k \)-surplus, then

\[
D_A = \{ v : U(G \setminus \{v\}) \not\subseteq U(G) \} \cup \{ v : |U(G \setminus \{v\})| < |U(G)| \}.
\]

As here the right hand side does not depend on \( A \), the set \( D_A \) is unique across the perfect node sets \( A \subseteq V(G) \) with \( k \)-surplus and thus equals \( D_G \). Finally we show that the uniqueness of \( D_A \) implies the uniqueness of \( A \). By definition, \( \Gamma(D_A) \subseteq A \). On the other hand, the \( k \)-surplus of \( A \) implies that \( A \subseteq \Gamma(D_A) \). Thus \( A = A_G \).

At this point the proof of Theorem 2.3 is straightforward using the results of this section.

**Proof of Theorem 2.3.** By Theorem 4.18, \( D = D_G \), and thus \( A = A_G \) and \( C = C_G \). Now the property 1 holds by definition. \( A_G \) is perfect with \( k \)-surplus, which is just tantamount to the properties 2 and 3. The property 4 follows from Lemma 4.16. \( \square \)
5 Matroidality and maximum weight packings

Definition 5.1. We say that the \( F \)-packing problem is \textit{matroidal} if for all graphs \( G \) those node sets \( X \subseteq V(G) \) which can be covered by an \( F \)-packing of \( G \) form a matroid.

Loebl and Poljak [15] express their belief that for graph sets \( F \) with \( K_2 \in F \) the \( F \)-packing problem is polynomial if and only if it is matroidal. This question is still open. That the condition \( K_2 \in F \) is indeed required was shown in [8], where it was proved that the \( k \)-piece packing problem for \( k \geq 2 \) is polynomial but not matroidal. This applies to the \( j \)-restricted \( k \)-matching problem for \( 0 \leq j < k \) as well, which is polynomial by [14], but not matroidal for \( j > 0 \), as shown by Theorem 2.4.

Proof of Theorem 2.4. Lemma 4.16 implies that the following considerations hold. Let

\[
\pi = \{ \{ v \} : v \notin W_A \} \cup \{ V(T) : T \text{ is a tip of a } (j,k)\text{-galaxy component of } G[D] \}.
\]

To create matroid \( P \), we make use of matroid \( M \) in the proof of Theorem 4.13. First, for each connected component \( H \) of \( G[D] \), replace \( H \) in \( M \) with \( \pi_H = \{ V(T) : T \text{ is a tip of } H \} \subseteq \pi \), such that the elements of \( \pi_H \) are in series with each other. Second, add as a direct sum the elements \( \{ v \} \) as bridges for \( v \notin W_A \). The resulting matroid is \( P \).

Let \( \text{def}(G) = c(G[D]) - k|A| \). The co-rank of \( M \) is \( \text{def}(G) \) thus the co-rank of \( P \) is \( \text{def}(G) \), too. Note that by Lemma 4.16 for each maximal \( j \)-restricted \( k \)-matching \( M \) of \( G \), every node set of \( \pi \) is either fully covered or fully missed by \( M \) and the number of the fully missed node sets is \( \text{def}(G) \). In the case \( j = 0 \), a tip has exactly one node so \( \pi \) is the partition into singletons. A special case is the classical matching problem for \( j = 0, k = 1 \). For \( j > 0 \), a tip has at most \( j \) nodes so the node sets of \( \pi \) are of size at most \( j \).

Because the ground set of the matroid \( P \) is a partition into different size sets, in the \( j \)-restricted \( k \)-matching problem a \textit{maximal} packing is not necessarily \textit{maximum}, as it is the case in the known polynomial packing problems with \( K_2 \in F \).

Theorem 2.5 on the characterization of the maximum weight \( j \)-restricted \( k \)-matchings was first proved in [14]. It can be deduced from the properties of matroid \( P \) as follows.

Proof of Theorem 2.5. Let us take the maximum weight bases of \( P \) with the weight function \( X \mapsto \sum \{ w(v) : v \in X \} \) for \( X \in \pi \). Now the maximum weight bases of \( P \) correspond to the maximum weight \( j \)-restricted \( k \)-matchings. So one can apply the greedy algorithm to find the maximum weight \( j \)-restricted \( k \)-matchings, which yields the formula in the statement.

Clearly, \( A_1 \) in Theorem 2.5 can be chosen to be the barrier \( A \) in the canonical decomposition. In the case \( k = 1 \) we get the Berge-theorem on maximum matchings [1].
We remark that our approach provides an alternative polynomial time algorithm to find a maximum weight $j$-restricted $k$-matching. First, the Edmonds-Gallai decomposition $V(G) = D \cup A \cup C$ for the $k$-piece packing problem can be determined in polynomial time [8, 10]. Theorem 4.18 and the construction in Theorem 4.13 shows that the canonical decomposition $V(G) = D \cup A \cup C$ for the $j$-restricted $k$-matching problem can be determined in polynomial time as well. With the greedy algorithm in the proof of Theorem 2.5 above these provide a polynomial time algorithm to find a maximum weight $j$-restricted $k$-matching for $0 \leq j < k$. As a counterpart, [14] proved that this problem is NP-complete for $j \geq k$.

One can construct the maximum weight packings in other ways as well. In [14] minimum cost flows are applied in the polynomial time alternating tree algorithm, while in [8] a direct argument is given for the $k$-piece packing problem.

6 Conclusions

An important relation between $k$-piece packings and $j$-restricted $k$-matchings is that every $k$-piece is a $j$-restricted $k$-matching for every $0 \leq j < k$. Using this connection, in this paper we gave an alternative proof to Theorem 2.5 of Li [14], and we proved two new results on the $j$-restricted $k$-matching problem. Theorem 2.3 is an Edmonds-Gallai-type decomposition, and Theorem 2.4 is a characterization of the maximal $j$-restricted $k$-matchings.

We may consider a generalization of $j$-restricted $k$-matchings inspired by the $(l, u)$-piece packings defined in [8], where $l$ and $u$ are assumed to be constant functions on the nodes satisfying $0 \leq l \leq u$. This generalization is called $j$-restricted $(l, u)$-piece packing, where $l$, $j$, and $u$ are constants such that $0 \leq l \leq j < u$. A connected graph $G$ is called a $j$-restricted $(l, u)$-piece if (1) $\Delta(G) \leq u$, (2) $\deg_G(w) \geq l$ for some $w \in V(G)$, and (3) $|E(G)| > j$. It is easy to see that a $j$-restricted $k$-matching $(0 \leq j < k)$ is just a $j$-restricted $(0, k)$-piece packing. One can probably establish an Edmonds-Gallai-type decomposition for $j$-restricted $(l, u)$-piece packings with $0 \leq l \leq j < u$.

Another question is, given a graph and not necessarily non-negative node weights, whether one can solve the maximum node weight $j$-restricted $k$-matching problem ($1 \leq j < k$) in polynomial time. The same question is open for $k$-piece packings ($k \geq 2$).

References


