On the Cycle Augmentation Problem: Hardness and Approximation Algorithms*

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Abstract. In the k-Connectivity Augmentation Problem we are given a k-edge-connected graph and a set of additional edges called *links*. Our goal is to find a set of links of minimum cardinality whose addition to the graph makes it $(k+1)$-edge-connected. There is an approximation preserving reduction from the mentioned problem to the case $k = 1$ (a.k.a. the Tree Augmentation Problem or TAP) or $k = 2$ (a.k.a. the Cactus Augmentation Problem or CacAP). While several better-than-2 approximation algorithms are known for TAP, nothing better is known for CacAP (hence for k-Connectivity Augmentation in general).
As a first step towards better approximation algorithms for CacAP, we consider the special case where the input cactus consists of a single cycle, the *Cycle Augmentation* Problem (CycAP). This apparently simple special case retains part of the hardness of the general case. In particular, we are able to show that it is APX-hard.
In this paper we present a combinatorial $\left(\frac{3}{2}+\varepsilon\right)$-approximation for CycAP, for any constant $\varepsilon > 0$. We also present an LP formulation with a matching integrality gap: this might be useful to address the general case of the problem.

Keywords: Approximation algorithms · Connectivity augmentation · Cactus augmentation · Cycle augmentation.

1 Introduction

The basic goal of *Survivable Network Design* is to construct low cost networks that provide connectivity guarantees between pre-specified sets of nodes even after the failure of a few edges/nodes (in the following we will focus on the egde

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failure case). This has many applications, e.g., in transportation and telecommunication networks.

A relevant subclass of these problems is given by *Network Augmentation* problems. Here the goal is to *augment* a given graph $G = (V, E)$ by adding extra edges taken from a given set L (*links*), so as to satisfy given (edge-)connectivity requirements. Several such problems are NP-hard, and in most cases the best known approximation factor is 2 due to Jain [14].

In this paper we focus on the following k-Connectivity Augmentation Problem (k-CAP). Given a k-(edge)-connected[3] undirected graph $G = (V, E)$ and a collection L of extra edges (*links*), the goal is to find a minimum cardinality subset $A \subseteq L$ such that $G' = (V, E \cup A)$ is $(k+1)$-connected. Dinitz et al. [8] presented an approximation preserving reduction from this problem to the case $k = 1$ for odd k, and $k = 2$ for even k. This motivates a deeper understanding of the latter two special cases.

The case $k = 1$ is also known as the Tree Augmentation Problem (TAP). The reason for this name is that any 2-connected component of the input graph G can be contracted, hence leading to a tree. For this problem several better-than-2 approximation algorithms are known [1, 6, 9, 10, 13, 17, 20]. The case $k = 2$ is also known as the Cactus Augmentation Problem (CacAP) since, similarly to the previous case, the input graph can be assumed to be a cactus[4] [8]. However, here the best-known approximation factor is still 2 [14] (implying the same for k-CAP in general).

For all the mentioned problems it makes sense to consider the weighted version, where links have non-negative integral weights, and the goal is to find a minimum weight (rather than minimum cardinality) subset of links A with the desired properties. In particular we will speak about Weighted TAP (WTAP) and Weighted CacAP (WCacAP). Here the best-known approximation factor is 2 in both cases [14]. Moreover, improving on that approximation factor for WTAP is considered as a major open problem in the area. We also notice that we can turn a WTAP instance into an equivalent WCacAP instance by replacing each edge with two parallel edges. Hence, approximating WCacAP is not any easier than approximating WTAP (and the same holds for the corresponding unweighted versions).

1.1 Our Results

As mentioned before, CacAP contains TAP as a special case when the cactus consists of several short cycles. Hence, in order to make progress on CacAP, it makes sense to consider the somehow complementary case where the input cactus consists of a single cycle of n nodes. We call the corresponding subproblem

[3] We recall that $G = (V, E)$ is k-connected if for every set of edges $F \subseteq E$, $|F| \leq k-1$, the graph $G' = (V, E \setminus F)$ is connected.

[4] We recall that a *cactus* G is a connected undirected graph in which every edge belongs to exactly one cycle. For technical reasons it is convenient to allow cycles of length 2 consisting of parallel edges.

the Cycle Augmentation Problem (CycAP), and its weighted version Weighted CycAP (WCycAP). To the best of our knowledge, these special cases were not studied before. However, as we will see, they still retain part of the difficulties of the general cactus case. In more detail, we achieve the following main results.

Hardness of Approximation. We are able to show that WCycAP is as hard to approximate as WCacAP. Therefore, improving on a 2-approximation for WCycAP would imply a major breakthrough in the area (in particular, it would imply the same for WTAP). This also justifies a more careful investigation of CycAP. In our opinion it is a priori not so obvious that CycAP is even NP-hard. Indeed, the special case of TAP (and even of WTAP) where the input graph is a path can be solved exactly in polynomial time. The case of an input cycle might closely remind the path case. Here we show that this intuition is not correct: we prove that CycAP is NP-hard and even APX-hard via a simple but non-trivial adaptation of the proofs in [11, 16]. In particular, we need one extra step in the reduction where we turn an intermediate CacAP instance into a CycAP one while maintaining certain properties of the optimal solution.

Approximation Algorithms. As discussed, the best we can hope for CycAP is some constant $c > 1$ approximation. We present better-than-2 approximation algorithms for this problem. In particular, we present a simple $\frac{5}{3}$-approximation, and a slightly more complex $(3/2 + \varepsilon)$-approximation for any constant $\varepsilon > 0$. Notice that the latter approximation factor is not far from the best known approximation factor for TAP which is equal to 1.458 [13]. Our algorithms are purely combinatorial, and they consist of two main phases. In the first phase, we *greedily* add some links to the solution under construction and *contract* them. At the end of this phase we achieve an instance of CacAP that can be solved exactly in polynomial time. In particular, for the $\frac{5}{3}$-approximation this reduces to computing a spanning tree, while for the $(3/2 + \varepsilon)$-approximation we use an FPT algorithm parameterized by a proper notion of maximum *length* of a link.

LP Gaps. The recent literature on TAP approximation [1, 10, 13] shows that finding strong LP relaxations for the problem can be very helpful to design improved approximation algorithms. In the same spirit, we tried to address the problem of finding LP relaxations for CycAP with small integrality gap. For both TAP and CacAP (hence CycAP) one can define a natural and simple standard cut LP (more details later). While for TAP it was recently shown that the standard cut LP has integrality gap smaller than 2 [21], interestingly for CycAP (hence for CacAP) the standard cut LP has integrality gap 2. Here we present a stronger LP that, for any $\varepsilon > 0$, has integrality gap at most $\frac{3}{2} + \varepsilon$ (hence matching the approximation ratio of our algorithm). In our opinion this could be useful for future work on CacAP approximation.

1.2 Related Work

As mentioned before, the best known result in terms of polynomial time approximation algorithms for k-CAP is a 2-approximation proposed by Jain [14].

However, if the set of links is equal to $V \times V$ it is possible to solve this problem optimally [22]. More recently, this problem has been studied in the framework of Fixed-Parameter Tractability: Végh and Marx [19] proved that this problem is in FPT when parameterized by the size of the optimal solution, and later the running time of their algorithm was further improved [2].

Tree Augmentation has been extensively studied over the past few decades. It was first shown that WTAP is NP-hard by Frederickson and Jájá [11], then that TAP is NP-hard by Cheriyan et al. [5], and later that TAP is APX-hard by Kortsarz et al. [16]. For WTAP, the best-known approximation guarantee is 2 and was first established by Frederickson and Jájá [11]. Their algorithm was later simplified by Khuller and Thurimella [15]. A 2-approximation can also be achieved by various other techniques developed later on, including a primal-dual approach [12] and iterative rounding [14]. Improvements on the factor 2 have only been obtained for restricted cases, including bounded diameter trees [7] and bounded weights [1, 10, 13, 21].

Regarding TAP, the first algorithm beating the approximation guarantee of 2 is due to Nagamochi [20], achieving an approximation factor of $1.815 + \varepsilon$. This factor was subsequently improved to 1.8 [9] and to 1.5 [6, 17]. These results are combinatorial in nature, but LP-based results have been achieved as well. As an example, recently Nutov [21] showed that the standard cut LP for TAP has an integrality gap of at most 28/15 while a lower bound of 3/2 was known [6]. An LP-based $\left(\frac{5}{3} + \varepsilon\right)$-approximation was given by Adjiashvili [1] and then refined by Fiorini et al. [10] to obtain a $\left(\frac{3}{2} + \varepsilon\right)$-approximation (see also [3, 4, 18]). Both results are obtained by adding a proper family of extra constraints to the standard cut LP. Recently, Grandoni et al. [13] achieved a 1.458 approximation for TAP, which is smaller than the integrality gap of the standard cut LP.

The rest of this paper is organized as follows. In Section 2 we give some preliminary definitions and results. The approximation algorithms, LP-gaps are discussed in Sections 3 and 4. Due to space limitations, some of the results and proofs are deferred to the full version of the paper.

2 Preliminaries

For a set X and element y, we use the shortcut $X \setminus y$ for $X \setminus \{y\}$, and similarly for other set operations.

Given a graph $G = (V, E)$, we let $V(G) = V$ and $E(G) = E$. Recall that in WCacAP we are given a cactus $G = (V, E)$, a set of links $L \subseteq \binom{V}{2}$ and a non-negative weight function $c : L \to \mathbb{R}_{\geq 0}$. The task is to compute a subset of links $A \subseteq L$ such that the graph $(V, E \cup A)$ is 3-edge-connected while minimizing $c(A) := \sum_{\ell \in A} c(\ell)$. The special case where G is a cycle is called WCycAP, and the unweighted versions of the above problems are called CacAP and CycAP respectively. By n we will denote the number of nodes of the considered instance of the problem.

Notice that, given an instance (G, L) of CacAP, we can check in polynomial time if the graph $(V(G), E(G) \cup L)$ is 3-edge-connected by exhaustively checking if the removal of any pair of elements from $E(G) \cup L$ disconnects the graph. Hence we will assume along this work that the instance always admits a feasible solution.

Remark 1. The 2-edge cuts of a cactus G are identified by pairs $S = \{e, e'\}$ of distinct edges belonging to the same cycle, and consist of the node sets (V', V'') of the two connected components obtained by removing S from G. A necessary and sufficient condition for a subset of links A to be a feasible solution for WCacAP is that, for any such cut S, there is at least one $\ell \in A$ crossing the cut (in which case ℓ **satisfies** the $\{e, e'\}$-cut).

Note that in the case of CycAP, Remark 1 implies that any feasible solution must be an edge cover as 2-edge cuts defined by neighboring edges of the cycle must be satisfied. Given a 2-edge cut $S = \{e, e'\}$, let L_S be the subset of links satisfying S. The standard cut LP for CycAP is as follows:

$$\begin{aligned} \min \sum_{\ell \in L} x_\ell & \qquad \text{(standard cut LP)} \\ s.t. \sum_{\ell \in L_S} x_\ell \geq 1 & \qquad \forall S : S \text{ is a 2-edge cut} \\ 0 \leq x_\ell \leq 1 & \qquad \forall \ell \in L \end{aligned}$$

Now we proceed to define a standard building block for our algorithms, the *contraction* of a link.

Definition 1. *Contracting a subset of nodes W consists of the following operations: (i) remove the nodes in W and all edges/links incident to them; (ii) add a new node w and, for each original edge/link of type (y, x), $x \in W, y \notin W$, add the edge/link (y, w) (of the same weight for the case of links). Note that we do not create loops this way but may introduce parallel links. We say that (y, w) is the image of (y, x) and (y, x) is the preimage of (y, w).*

We will sometimes slightly abuse notation and use the same label to denote a link and its image: the meaning will be clear from the context.

For a link $\ell = (u, v)$, we define a sequence $w_0, \ldots, w_q$ of boundary nodes $B(\ell)$ as follows. Consider a simple path from u to v in the cactus, and let $C_1, C_2, \ldots, C_q$ be the ordered sequence of cycles visited[5] by this path (possibly $q = 1$). We define w_i, $i = 1, \ldots, q-1$ as the unique common node between C_i and C_{i+1}, and set $w_0 = u$ and $w_q = v$.

Definition 2. *Contracting a link ℓ is the operation of contracting its boundary nodes $B(\ell)$. We denote by $G|\ell$ the graph obtained by this operation. Contracting a set of links A is the operation of contracting any $\ell \in A$, and then continue recursively on $G|\ell$ and on the image of $A \setminus \ell$ until A becomes empty.*

[5] A path visits a cycle iff it includes an edge from the cycle.

Note that contracting a link in a cactus yields again a cactus. We will extensively use the following standard fact, whose proof is given in the full version of the paper.

Lemma 1. *Let (G, L) be a CacAP instance, $A \subseteq L$, and $\ell \in A$. Then A is a feasible solution for (G, L) iff the image of $A \setminus \ell$ is a feasible solution for $(G|\ell, L \setminus \ell)$.*

3 Approximation Algorithms for Cycle Augmentation

In this section we present improved approximation algorithms for CycAP. We start with a simple $\frac{5}{3}$-approximation to illustrate the main ideas, and then present a slightly more complex $\left(\frac{3}{2} + \varepsilon\right)$-approximation. The approach we will follow in both cases is as follows: in a first phase we iteratively add a properly chosen subset of a few links to the solution under construction, and then contract them. Notice that, after the first contraction, the cycle structure may be lost and we obtain a CacAP instance instead. These choices are designed so that, at the end of the first phase, the remaining CacAP instance can be solved efficiently, which is done in a second phase with an ad-hoc algorithm. We remark that the running times of the presented algorithms is not analyzed in detail, and indeed such a task may require to devise carefully crafted data structures.

3.1 A $\frac{5}{3}$-approximation

We next describe a simple greedy algorithm that provides a $\frac{5}{3}$-approximation for CycAP. We need the following definitions.

Definition 3. *A link $\ell = (u, v)$ of a CacAP instance is **internal** if both its endpoints belong to a common cycle, and* external *otherwise.*

Definition 4. *Given a CacAP instance, a pair of internal links $\{(u_1, v_1), (u_2, v_2)\}$ of a cycle C is **crossing** if they are node disjoint and deleting u_2 and v_2 disconnects u_1 from v_1 in C.*

The kind of links that we want to add in the first stage of the algorithm are external links plus crossing pairs of links. More in detail, the algorithm has two main stages. The first stage consists of a set of rounds, where in each round we first check if there exists an external link ℓ, in which case we add it to our solution, contract it and proceed to the next round. Otherwise, if there exists a pair of (internal) crossing links ℓ' and ℓ'', we add them to our solution, contract them and proceed to the next round. If none of the two cases above applies, we are left with a CacAP instance without neither external links nor crossing pairs of links which we address in the second stage of the algorithm. We refer to this algorithm as CROSSING-FIRST. As the following lemma states, in the second stage we can efficiently compute the optimal solution.

Lemma 2. *Consider an instance $(G = (V, E), L)$ of CacAP. If there are no external links and no crossing pairs of links, then every minimal solution has size exactly $|V| - 1$ and induces a spanning tree over V.*

Proof. We prove the first part of the claim by induction on $n = |V|$. The base case $n = 2$ is trivial since in this case the instance is just a cycle consisting of two parallel edges and any link must be incident to the two nodes of G (hence defining a feasible solution). For the inductive case, assume the claim is true up to instances having $n-1$ nodes, and consider an instance of the problem defined by a cactus G having n nodes with optimal solution OPT. If G is not a cycle of length n, then it is defined by a set of cycles of length at most $n-1$ where every link is internal, so we can apply the inductive hypothesis to each cycle independently. If G is a cycle of n nodes, then let $\ell = (u, v) \in \text{OPT}$. Contracting ℓ leads to a CacAP instance on two cycles C_1 and C_2 sharing a common node w, with $|V(C_1)| + |V(C_2)| = n$. Let OPT' be the optimal solution for the new instance. By Lemma 1, $|\text{OPT}| = |\text{OPT}'| + 1$. Observe that any remaining link ℓ' must have both endpoints in the same C_i (otherwise ℓ and ℓ' would be crossing). Thus by the inductive hypothesis the optimum solution for the problem induced by C_i has size $|V(C_i)| - 1$. It then follows that $|\text{OPT}'| = |V(C_1)| - 1 + |V(C_2)| - 1 = n - 2$. Hence $|\text{OPT}| = n - 1$ as desired.

For the second part of the claim, it is sufficient to show that a minimal solution does not induce a cycle. By contradiction, consider a minimal solution containing a simple cycle L', and consider now a solution where we remove precisely one arbitrary link $\ell = (u, v)$ from L'. Consider any pair of edges e_1, e_2 belonging to the same cycle such that ℓ satisfies the $\{e_1, e_2\}$-cut. Since $L' \setminus \ell$ induces a simple u-v path, then some $\ell' \in L' \setminus \ell$ must satisfy the cut. Thus $L' \setminus \ell$ is a feasible solution, contradicting the minimality of L'.

Now we proceed to prove the approximation guarantee of the algorithm.

Theorem 1. *The* CROSSING-FIRST *algorithm is a $\frac{5}{3}$-approximation for CycAP.*

Proof. Let OPT be the optimal solution and APX the computed solution. Let also n'' be the number of nodes remaining at the end of the first stage, and APX' (resp. APX'') be the set of links added to the solution during the first (resp. second) stage. Since contracting an external link decreases the number of nodes by at least 2 and contracting any pair of crossing links decreases the number of nodes by at least 3, we have that $|\text{APX}'| \leq \frac{2}{3}(n - n'')$.

By Lemma 2, $|\text{APX}''| = n'' - 1$, and hence $|\text{APX}| \leq \frac{2}{3}(n - n'') + n'' - 1 = \frac{2n+n''-3}{3}$. On the other hand, since any feasible solution must be an edge cover, we have that $|\text{OPT}| \geq n/2$. Observe also that $|\text{OPT}| \geq n'' - 1$ since by Lemma 1 contracting links cannot increase the cost of the optimum solution. Thus $|\text{OPT}| \geq \max\{n/2, n''-1\}$. We can conclude that $\frac{|\text{APX}|}{|\text{OPT}|} \leq \frac{(2n+n''-3)/3}{\max\{n/2, n''-1\}} \leq \frac{5}{3}$, being $n'' - 1 = n/2$ the worst case.

We complement this result with an asymptotically matching lower bound.

Lemma 3. *The approximation ratio of the* CROSSING-FIRST *algorithm is not better than* $\frac{5}{3}$.

Proof. Consider the following construction: for each $k \geq 2$ consider an instance (G_k, L_k) of CycAP defined by a cycle of $n = 6k$ nodes (assume that the cycle is defined by the order of the nodes $v_1, v_2, \ldots, v_{6k}$) and the following set of links (see Figure 1 (Left)):

- $(v_1, v_{\frac{n}{2}+1}) \in L_k$;
- For each $i = 1, \ldots, \frac{n}{2} - 1$, $(v_{i+1}, v_{n+1-i}) \in L_k$;
- For each $i = 1, \ldots, \frac{n}{6}$, $(v_{3(i-1)+1}, v_{3(i-1)+3}) \in L_k$ and $(v_{3(i-1)+2}, v_{3(i-1)+4}) \in L_k$;

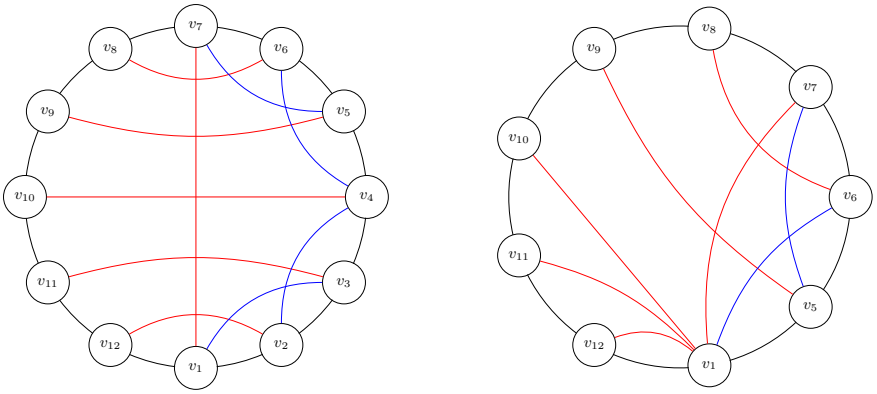

Fig. 1. Left: Instance (G_2, L_2) from the lower bound construction in Lemma 3. Red links define an optimal solution. **Right**: If the algorithm in the first phase picks and contracts the crossing links $\{(v_1, v_3), (v_2, v_4)\}$, this is the obtained CacAP instance.

Notice that the first and second set of links define a feasible solution of size $\frac{n}{2}$, hence being optimal: if we remove any two edges of the cycle, then we are either satisfying the corresponding cut via $(v_1, v_{\frac{n}{2}+1})$, or one side of the partition is contained in either $\{v_2, \ldots, v_{\frac{n}{2}}\}$ or in $\{v_{\frac{n}{2}+2}, \ldots, v_n\}$ but the links selected form a matching between those sets.

We will now prove that there exists a sequence of choices performed by our algorithm that outputs a solution of size $\frac{5n}{6} - 1$, which implies that the approximation ratio is at least $\frac{5}{3} - \frac{2}{n}$ and this value approaches $\frac{5}{3}$ as k goes to infinity. Notice first that the pair of links $\{(v_1, v_3), (v_2, v_4)\} \subseteq L_k$ is crossing, and hence the algorithm can include them in the solution in the first round (and finish the round). Furthermore, after these links are contracted no link becomes external as the new cactus instance consists of a cycle of length $n - 3$, and also the links with endpoints v_n, v_{n-1} and v_{n-2} are not part of any pair of crossing links (see Figure 1 (Right)). If we now iteratively pick all the pairs of crossing links $\{(v_{3(i-1)+1}, v_{3(i-1)+3}), (v_{3(i-1)+2}, v_{3(i-1)+4})\} \subseteq L_k$, $i = 2, \ldots, \frac{n}{6}$, after $\frac{n}{6}$ rounds we end up with a cycle of length $\frac{n}{2}$ without crossing links, and the algorithm

must now take the remaining $\frac{n}{2} - 1$ links to complete the solution. Thus, the size of the computed solution is $2 \cdot \frac{n}{6} + \frac{n}{2} - 1 = \frac{5}{6}n - 1$, proving the claim.

3.2 A $\left(\frac{3}{2} + \varepsilon\right)$-approximation

The family of instances from Lemma 3 suggests that "short" crossing pairs of links, although being locally profitable, may enforce the algorithm to take expensive decisions in the end. In this section we present a more involved $\left(\frac{3}{2} + \varepsilon\right)$-approximation for CycAP that tries to avoid this kind of situation. Like in the previous algorithm, there is a certain kind of links that we want to iteratively add to our solution in a first phase, and in this case such links correspond to external links and *long* links, which are defined as follows.

Definition 5. *The* ***length*** *of an internal link (u, v) is the length of the shortest path between u and v in the corresponding cycle. For a given parameter $0 < \varepsilon < 1$, an internal link is called* ***long*** *if its length is at least $\frac{1}{\varepsilon}$, and* ***short*** *otherwise.*

Our algorithm consists of the following two main phases. In the first phase, we iteratively check if there exists a long (internal) link ℓ. Otherwise, we check if there exists an external link ℓ. In both cases, we add ℓ to the solution under construction and contract it. Observe that contracting links does not create new long links, hence we will first select a set L_{long} of long links, and then a set L_{ext} of external links.

After exhausting the previous choices, we move to the second phase. Here we are left with an instance where all links are short and internal, so we can solve independently the sub-instance induced by each cycle. We refer to this algorithm as LONG-FIRST. This second stage can be solved efficiently, due to the lack of long links, by means of the following lemma[6].

Lemma 4. *Given a CycAP instance, there exists an algorithm that returns the optimal solution in time poly$(n) \cdot 2^{O(h_{\max}^2)}$, where $h_{\max}$ is the maximum length among the links.*

Let L_{short} be the collection of edges obtained in the second stage. The final solution is $L_{\text{long}} \cup L_{\text{ext}} \cup L_{\text{short}}$.

Theorem 2. *The previous algorithm is a $(\frac{3}{2} + \varepsilon)$-approximation algorithm for CycAP.*

Proof. The running time of the algorithm is upper-bounded by $\text{poly}(n)2^{O(1/\varepsilon^2)}$. Consider next the approximation factor. Note first that $|L_{\text{long}}| \leq \varepsilon n$. Indeed, contracting a long link always increases the number of cycles in the cactus by one without decreasing the number of edges, and all these cycles always have size at least $1/\varepsilon$, so there are at most εn of them. Similarly to Theorem 1, we have that $|\text{OPT}| \geq |L_{\text{short}}|$ and $|\text{OPT}| \geq \frac{n}{2}$.

[6] This lemma implies that CycAP is FPT with parameter $h_{\max}$.

If $|L_{\text{long}}|+|L_{\text{ext}}|+|L_{\text{short}}| \leq \frac{(3+2\varepsilon)n}{4}$ then we already have a $\left(\frac{3}{2}+\varepsilon\right)$-approximation as $|\text{OPT}| \geq \frac{n}{2}$. Otherwise, since the contraction of each external link reduces the number of nodes by at least 2 and the contraction of any other link reduces the number of nodes by at least 1, we have that $|L_{\text{long}}| + 2|L_{\text{ext}}| + |L_{\text{short}}| \leq n$. So $|L_{\text{ext}}| \leq n - \frac{(3+2\varepsilon)n}{4} = \frac{(1-2\varepsilon)n}{4}$ and hence $|L_{\text{ext}}| + |L_{\text{long}}| \leq \frac{n+2\varepsilon n}{4} \leq \left(\frac{1}{2}+\varepsilon\right)|\text{OPT}|$. Since $|\text{OPT}| \geq |L_{\text{short}}|$, we have that in this case the size of the solution is also at most $(\frac{3}{2}+\varepsilon)|\text{OPT}|$, concluding the proof.

Remark 2. By replacing ε with $1/\sqrt{\log n}$ in the above construction, we can obtain a slightly improved approximation factor of $3/2 + o(1)$ which still runs in polynomial time.

It remains to prove Lemma 4. We need some more notation. Recall that a 2-cut $\{e, e'\}$ is satisfied iff there is some link crossing the cut. Given a link $\ell = (u, v)$, we say that the edges of the shortest path between u and v in the cycle are *covered* by ℓ (in case of multiple shortest paths we choose the one going from u to v in counter-clockwise order along the cycle). Given an edge e of the cycle, we define the *cut-neighborhood* of e, namely $\mathcal{N}(e)$, as the $2h_{\max} - 1$ edges that are closest to e, e included. We also define $\mathcal{N}_L(e)$ as the set of links in L covering at least one edge from $\mathcal{N}(e)$.

Notice that in any feasible solution to a CycAP instance, at most one edge of the cycle is not covered: if it is not the case, then the cut defined by two uncovered edges is not satisfied as any link satisfying the cut would cover one of these two edges. We can use this observation to characterize the feasibility of a solution in terms of the cut-neighborhoods.

Lemma 5. *Consider a CycAP instance and let A be a set of links such that every edge of the cycle is covered by some link in A. A is feasible iff for each edge e, all the $\{e, e'\}$-cuts, where $e' \in \mathcal{N}(e)$, are satisfied.*

Proof. If A is feasible then the required properties are clearly satisfied since every cut is satisfied. On the other hand, suppose that A satisfies that every edge is covered by some link in A and the $\{e, e'\}$-cuts are satisfied for every edge e and $e' \in \mathcal{N}(e)$. Consider a pair of edges $\{e, e'\}$ such that $e' \notin \mathcal{N}(e)$. By definition of $\mathcal{N}(e)$ there is no link in A covering both edges at the same time, and as e is covered by some link, this link satisfies the $\{e, e'\}$-cut. This implies that A is feasible as every cut is satisfied.

This lemma is useful as it implies that, given an edge e and a set of links S, we can optimally complete S in order to satisfy every $\{e, e'\}$-cut in time $2^{O(h_{\max}^2)}$ just by guessing the subset of links from $\mathcal{N}_L(e)$ that must be added, which are $O(h_{\max}^2)$ only. Now we proceed to present the algorithm.

Proof (Proof of Lemma 4).

Let us assume that we deal with instances of CycAP such that there exists an optimal solution where every edge is covered by some link. If it is not the case, as there may be only one uncovered edge, we can guess this edge and contract it;

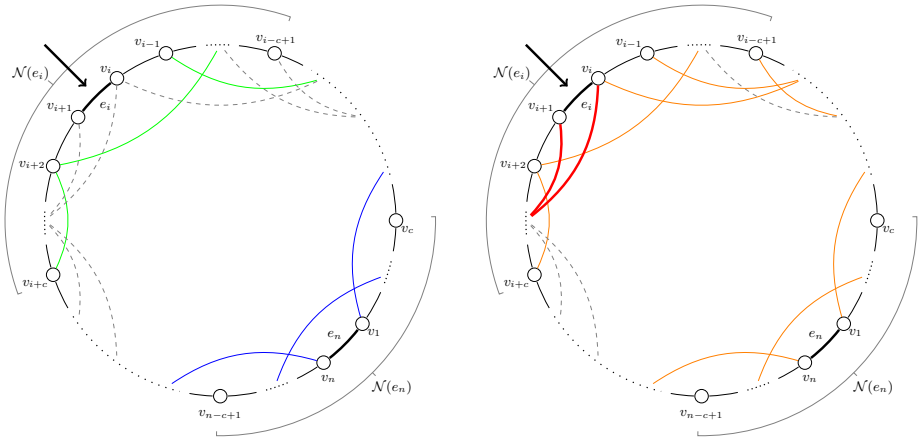

Fig. 2. Depiction of an iteration of the DP from Lemma 4, where we are currently at edge e_i. **Left**: Blue links correspond to L_0, green links correspond to S and at this point we must decide which extra links to add to $S \cup L_0$ in order to satisfy the edges $e_1, \ldots, e_i$. **Right**: This computation is done by looking at a proper previous cell in the table (orange links) which contains $S \cup L_0$ and satisfies $e_1, \ldots, e_{i-1}$, and then add the extra required links A^* (red links) in order to satisfy e_i too.

this leads to an equivalent instance of the problem where we can require that the optimum solution covers all the edges. We say that an edge e is *satisfied* by a set of links A if it is covered by some link in A and furthermore every $\{e, e'\}$-cut is satisfied by A. In particular A is a feasible solution for the problem iff it satisfies all the edges.

We next design a dynamic programming algorithm to compute a minimum cardinality feasible solution. Let us name the nodes $v_1, v_2, ..., v_n$ in counter-clockwise order starting from some arbitrary node v_1, and let the edges be $e_i = (v_i, v_{i+1})$ for each $i = 1, \ldots, n$ (assuming $v_{n+1} = v_1$). We start first by guessing the set L_0 of links from OPT that satisfy e_n. As proved in Lemma 5, L_0 is a subset of $\mathcal{N}_L(e_n)$, hence we can guess it in time $2^{O(h^2_{\max})}$.

For each edge e_i and $S \subseteq \mathcal{N}_L(e_i)$, we define a cell $T[i][S]$ which will correspond to a set S' of links of smallest cardinality such that for each $j \in \{1, \ldots, i\}$, e_j is satisfied by S', subject to $L_0 \cup S \subseteq S'$. It is then sufficient to return $T[n][\emptyset]$.

We initialize the table by computing $T[1][S]$ for each set $S \subseteq \mathcal{N}_L(e_1)$, which can be done by guessing how to complete $S \cup L_0$ in order to satisfy e_1 with links from $\mathcal{N}_L(e_1)$. Then, for each $i \geq 2$ and $S \subseteq \mathcal{N}_L(e_i)$, in order to fill the cell $T[i][S]$, we consider all the possible subsets $A \subseteq \mathcal{N}_L(e_i)$ such that $S(A) := T[i-1][(S \cup A) \cap \mathcal{N}_L(e_{i-1})] \cup (S \cup A)$ satisfies e_i. Among them we select a set A^* that minimizes $|S(A)|$, and we set $T[i][S] = S(A^*)$ (see Figure 2 for a sketch).

The correctness of the computation follows by a simple induction on i. The table can be filled in total time $\text{poly}(n) \cdot 2^{O(h^2_{\max})}$, plus an extra factor n from the initial guessing of an uncovered edge (that is contracted).

We complement Theorem 2 with an asymptotically matching lower bound.

Lemma 6. *The approximation ratio of the* LONG-FIRST *algorithm is at least* $\frac{3}{2}$.

Proof. Consider the following construction: for each $k > \frac{1}{2\varepsilon}$ consider an instance (G_k, L_k) of CycAP defined by a cycle of $n = 4k$ nodes (assume that the cycle is defined by the order of the nodes $v_1, v_2, \ldots, v_{4k}$) and the following set of links (see Figure 3 (Left)):

- For each $i = 1, \ldots, \frac{n}{2} - 1$, $(v_{i+1}, v_{n+1-i}) \in L_k$;
- $(v_1, v_{\frac{n}{2}+1}) \in L_k$;
- For each $i = 1, \ldots, \frac{n}{4} - 1$, $(v_{i+1}, v_{\frac{n}{2}+1-i}) \in L_k$.

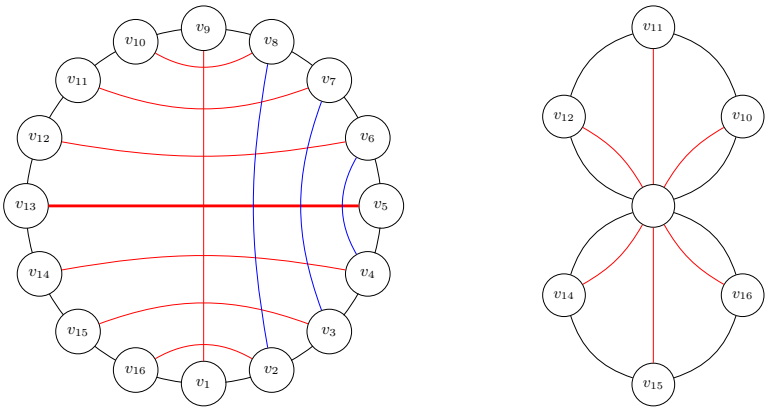

Fig. 3. Left: Instance (G_4, L_4) from the lower bound construction in Lemma 6. An optimal solution is defined by red links. **Right**: If the algorithm picks first the thick red link (which is long) and then the links which become external (blue links and (v_1, v_9)) we obtain this subinstance without crossing pairs of links.

As argued in Lemma 3, the first and second set of links define an optimal solution of size $\frac{n}{2}$. We will now prove that there exists a sequence of choices performed by our algorithm that outputs a solution of size $\frac{3n}{4} - 1$, which implies that the approximation ratio is at least $\frac{3}{2} - \frac{2}{n}$ and this value approaches $\frac{3}{2}$ as k goes to infinity. Notice first that the link $(v_{\frac{n}{4}+1}, v_{\frac{3n}{4}+1}) \in L_k$ has length $2k > \frac{1}{\varepsilon}$ and hence it is long so the first stage of the algorithm can include it in the solution. After doing that, the second and third set of links become external and thus the algorithm will include them in the solution. Once all these links are included and contracted, we get a cactus consisting of two cycles of $\frac{n}{4}$ nodes each and without crossing links (see Figure 3 (Right)). Hence, the algorithm must pick all the remaining links to complete the solution. The size then of this solution is $\frac{n}{4} + 1 + 2\left(\frac{n}{4} - 1\right) = \frac{3n}{4} - 1$.

4 LP Relaxations for CycAP

We start by lower-bounding the integrality gap of the standard cut LP for CycAP.

Lemma 7. *The standard cut LP for CycAP has integrality gap at least* 2.

Proof. Consider a cycle of size k and, for each edge, a parallel link. The optimum integral solution has size $k-1$, while setting each variable to $\frac{1}{2}$ gives a feasible fractional solution of cost $\frac{k}{2}$.

This shows that the standard cut LP is not strong enough even for instances without crossing nor long links, cases that we can handle optimally via combinatorial algorithms. We next present a stronger LP that exploits a more general set of constraints.

Let $(G = (V, E), L)$ be a CycAP instance and $S \subseteq E$. We define the *S-reduced* instance (G_S, L_S) as follows: We contract the edges of $E \setminus S$, obtaining a cycle with $|S|$ edges which defines G_S, and the set of links L_S will correspond to the images of L. Notice that there is a one-to-one relation between L_S and the links in L which satisfy some cut defined by a pair of edges from S. We denote by OPT_S the optimal solution for the instance (G_S, L_S)[7]. The following lemma characterizes the feasibility of a solution.

Lemma 8. *Given an instance (G, L) of CycAP, a solution $A \subseteq L$ is feasible iff for every $S \subseteq E$ it holds that $|A \cap L_S| \geq |\mathrm{OPT}_S|$.*

Proof. Suppose that there exists $S \subseteq E$ such that $|A \cap L_S| < |\mathrm{OPT}_S|$. This means that $A \cap L_S$ is not a feasible solution for (G_S, L_S) and hence there exist two edges $e_i, e_j \in S$ such that no link in $A \cap L_S$ satisfies the $\{e_i, e_j\}$-cut. As the remaining links in $A \setminus L_S$ also do not satisfy the cut by definition, this cut remains unsatisfied in the original instance, implying that A is not feasible.

On the other hand, suppose that A satisfies the claimed property for every set S. If we consider just sets S consisting of two edges this is exactly the characterization of feasibility shown in Remark 1, implying that A is feasible.

This implies that we can add the constraint $\sum_{\ell \in L_S} x_\ell \geq |\mathrm{OPT}_S|$ for $S \subseteq E$. Unfortunately there is an exponential number of such constraints and most of them require to compute $|\mathrm{OPT}_S|$ for large instances. However, if we restrict ourselves to sets of edges having constant size, we get an LP formulation with polynomially many constraints that can be written in polynomial time. We call this LP the k-edge-cut LP for a given constant $k \in \mathbb{N}$, which is similar in spirit to the *bundle-LP* for TAP introduced by Adjiashvili [1].

$$\begin{aligned} \min \sum_{\ell \in L} x_\ell & \qquad (k\text{-edge-cut LP}) \\ s.t. \sum_{\ell \in L_S} x_\ell \geq |\mathrm{OPT}_S| & \qquad \forall S \subseteq E, |S| \leq k \\ 0 \leq x_\ell \leq 1 & \qquad \forall \ell \in L \end{aligned}$$

[7] For $|S| \leq 1$, we simply set $\mathrm{OPT}_S = \emptyset$.

Notice that for $k = 2$ this is exactly the standard cut LP. Now we will prove some properties of this relaxation and bound its integrality gap.

Lemma 9. *Given $\varepsilon > 0$, for $k = \frac{1}{\varepsilon^2}$ the k-edge-cut LP restricted to instances with links of length at most $\frac{1}{\varepsilon}$ has integrality gap at most $(1 + 2\varepsilon)$.*

Proof. We will assume w.l.o.g. that the set of links L contains every possible link of length 1. If it is not the case, let us include them obtaining a new set of links $L' \supseteq L$. The optimal LP value can only decrease while the size of the optimal solution cannot decrease, implying that the integrality gap can only increase due to this operation. To see this last fact, assume by contradiction that there exists a solution OPT' for the new instance having strictly smaller size than OPT. Consider now a solution S consisting of $\mathrm{OPT}' \cap L$ plus a minimal set of links from L that makes S feasible (this is possible since the instance admits a feasible solution). If we in parallel iteratively contract the common links in S and OPT' we arrive to the same CacAP instance, but now the remaining links from OPT' have length 1 and the contraction of each of them reduces the number of nodes in the instance by exactly one node while the contraction of the remaining links in S reduces the number of nodes by at least 1. Thus $|S| \leq |\mathrm{OPT}'|$ which is not possible since $S \subseteq L$.

Let $X = (x_\ell)_{\ell \in L}$ be an optimal solution for the k-edge-cut LP. We will construct an integral feasible solution of size at most $(1 + \varepsilon) \sum_{\ell \in L} x_\ell$. To do so, we will partition the cycle into disjoint intervals as follows: We will first define an interval of size k (which we will call a *long* interval) and then an interval of size $\frac{1}{\varepsilon}$ (which we will call a *short* interval), and then continue with this procedure until it is not possible to continue. If in the end there are at most $\frac{1}{\varepsilon}$ edges we define a last short interval consisting of these remaining edges, otherwise we define a short interval consisting of the last $\frac{1}{\varepsilon}$ edges and a long interval consisting of the remaining edges (which will have size at most k). The number of short intervals is upper bounded by $1 + \left\lfloor \frac{n}{1/\varepsilon^2 + 1/\varepsilon} \right\rfloor \leq 1 + \frac{\varepsilon^2 n}{1+\varepsilon} \leq \varepsilon^2 n$ assuming w.l.o.g. that n is lower bounded by a large enough constant.

Notice that $\sum_{\ell \in L} x_\ell \geq n/2$ by a simple averaging argument over the n constraints corresponding to all the pairs of consecutive edges: every link appears in exactly two such constraints and the right-hand side of each constraint is 1. Since the total number of links of length 1 having both endpoints in a short interval is at most $\varepsilon^2 n \cdot \frac{1}{\varepsilon} = \varepsilon n \leq 2\varepsilon \sum_{\ell \in L} x_\ell$, we can add them to our solution at a negligible cost.

Consider now the set of long intervals $S_1, S_2, \ldots, S_T$. Notice that no link has endpoints in different long intervals, and hence the LP constraints associated to such intervals do not share common variables. This implies that $\sum_{\ell \in L} x_\ell \geq \sum_{i=1}^{T} |\mathrm{OPT}_{S_i}|$. Our feasible solution will consist of all the links of length 1 with both endpoints in a short interval plus the optimal solutions OPT_{S_i} for each long interval S_i. As argued before, the size of this solution is at most $(1+2\varepsilon) \sum_{\ell \in L} x_\ell$ and the feasibility of the solution follows since every $\{e, e'\}$-cut where e is in a short interval is satisfied by a link of length 1, while the remaining cuts are satisfied by the links computed optimally.

Lemma 10. *Given $\varepsilon > 0$, for $k = \frac{1}{\varepsilon^2}$ the k-edge-cut formulation has integrality gap at most $(1 + 4\varepsilon)$ restricted to instances without crossing pairs of links.*

Proof. Let $X = (x_\ell)_{\ell \in L}$ be an optimal solution for the k-edge-cut LP. Suppose that the instance does not contain links of length at least $\frac{1}{\varepsilon}$, then we can conclude the claim thanks to Lemma 9. Otherwise, we will pick any link of length at least $\frac{1}{\varepsilon}$ and contract it, obtaining a CacAP instance consisting of two cycles without external links (as there are no crossing links), both of size at least $\frac{1}{\varepsilon}$. If any cycle still contains some long link, we iterate this procedure. Let L_{long} be the set of long links we picked during this procedure and $C_1, C_2, \ldots, C_T$ be the set of cycles at the end. By the same argument as in Theorem 2, we have that $|L_{\text{long}}| \leq \varepsilon n \leq 2\varepsilon \sum_{\ell \in L} x_\ell$.

If we apply now Lemma 9 to each cycle we obtain a feasible solution of size at most $(1+2\varepsilon)\sum_{i=1}^{T} \text{OPT}_{\text{LP}_i} + |L_{\text{long}}|$, where LP_i is the k-edge-cut LP defined by each cycle C_i and its internal links. As there are no external links, the sum of the previous LP solutions is the optimal solution for the following LP:

$$\begin{aligned} \min \quad & \sum_{\ell \in L \setminus L_{\text{long}}} x_\ell \\ s.t. \quad & \sum_{\ell \in L_S} x_\ell \geq |\text{OPT}_S| \ \forall i \in \{1, \ldots, T\}, \forall S \subseteq E(C_i), |S| \leq \tfrac{1}{\varepsilon^2} \\ & 0 \leq x_\ell \leq 1 \qquad \forall \ell \in L \setminus L_{\text{long}} \end{aligned}$$

The set of constraints of this LP is a subset of the constraints of the original LP as links in L_{long} do not appear in these constraints and the set of variables is a subset of the original one. Thus we have $\sum_{i=1}^{T} \text{OPT}_{\text{LP}_i} \leq \sum_{\ell \in L} x_\ell$, and then we can conclude that the constructed solution has size at most $(1+4\varepsilon)\sum_{\ell \in L} x_\ell$.

Following the proof of Theorem 2 plus the previous results we can get the following bound on the integrality gap for general instances of CycAP.

Corollary 1. *For any $\varepsilon > 0$, the integrality gap of the k-edge-cut LP for $k = \frac{1}{\varepsilon^2}$ is at most $\frac{3}{2} + O(\varepsilon)$.*

Proof. Let $X = (x_\ell)_{\ell \in L}$ be an optimal solution for the k-edge cut LP and consider the output of the $\left(\frac{3}{2} + \varepsilon\right)$-approximation from Section 3.2 decomposed into L_{long}, L_{ext} and L_{short} as in the proof of Theorem 2. As argued before, we know that $\sum_{\ell \in L} x_\ell \geq \frac{n}{2}$ and analogously to the proof of Lemma 10 we have that $|L_{\text{short}}| \leq (1 + 2\varepsilon)\sum_{\ell \in L} x_\ell$. Hence essentially the same analysis as in Theorem 2 provides the same bound of $3/2 + O(\varepsilon)$ up to an extra $(1 + \varepsilon)$ factor.

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