

Improved Inapproximability for TSP

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Abstract. The Traveling Salesman Problem is one of the most studied problems in computational complexity and its approximability has been a long standing open question. Currently, the best known inapproximability threshold known is $\frac{220}{219}$ due to Papadimitriou and Vempala. Here, using an essentially different construction and also relying on the work of Berman and Karpinski on bounded occurrence CSPs, we give an alternative and simpler inapproximability proof which also improves the bound to $\frac{185}{184}$.

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1 Introduction

The Traveling Salesman Problem (TSP) is one of the most widely studied algorithmic problems and deriving optimal approximability results for it has been a long-standing question. Recently, there has been much progress in the algorithmic front, after more than thirty years, at least in the important special case where the instance metric is derived from an unweighted graph, often referred to as Graphic TSP. The $\frac{3}{2}$ -approximation algorithm by Christofides was the best known until Gharan et al. gave a slight improvement [6] for Graphic TSP. Then an algorithm with approximation ratio 1.461 was given by Mömke and Svensson [9]. With improved analysis on their algorithm Mucha obtained a ratio of $\frac{13}{9}$ [10], while the best currently known algorithm has ratio 1.4 and is due to Sebö and Vygen [15].

Nevertheless, there is still a huge gap between the guarantee of the best approximation algorithms we know and the best inapproximability results. The TSP was first shown MAXSNP-hard in [14], where no explicit inapproximability constant was derived. The work of Engerbretsen [5] and Böckenhauer et al. [4] gave inapproximability thresholds of $\frac{5381}{5380}$ and $\frac{3813}{3812}$ respectively. Later, this was improved to $\frac{220}{219}$ in [13] by Papadimitriou and Vempala¹. No further progress has been made on the inapproximability threshold of this problem in the more than ten years since [12].

Overview: Our main objective in this paper is to give a different, less complicated inapproximability proof for TSP than the one given in [12, 13]. The proof of [13] is very much optimized to achieve a good constant: the authors reduce directly from MAX-E3-LIN2, a CSP for which optimal inapproximability results are known, due to Håstad [7]. They take care to avoid introducing extra gadgets for the variables, using only gadgets that encode the equations. Finally they define their own custom expander-like notion on graphs to ensure consistency between tours and assignments. Then the reduction is performed in essentially one step.

Here on the other hand we take the opposite approach, choosing simplicity over optimization. We also start from MAX-E3-LIN2 but go through two intermediate CSPs. The first step in our reduction gives a set of equations where each variable appears at most five times (this property will come in handy in the end when proving consistency between tours and assignments). In this step, rather than introducing something new we rely heavily on machinery developed by Berman and Karpinski to prove inapproximability for bounded occurrence CSPs [1–3]. As a second step we reduce to MAX-1-IN-3-SAT². The motivation is that the 1-IN-3 predicate nicely corresponds to the objectives of TSP, since we represent clauses by gadgets and the most economical solution will visit all gadgets once but not more than once. Another way to view this step is that we use MAX-1-IN-3-SAT as an aid to design a TSP gadget for parity. Finally, we put it all together and reduce from MAX-1-IN-3-SAT to TSP.

This approach is (at least arguably) simpler than the approach of [13], since some of our arguments can be broken down into independent pieces, arguing about the inapproximability of intermediate, specially constructed CSPs. We also benefit from re-using out-of-the box the amplifier construction of [3]. Interestingly, putting everything together we end up obtaining a slightly better constant than the one currently known, implying that there may still be some room for further improvement. Though we are still a long way from an optimal inapproximability result, our results show that there may still be hope for better bounds with existing tools. Exploring how far these

¹ The reduction of [13] was first presented in [12], which (erroneously) claimed a better bound.

² In fact it might be more appropriate to call this problem MAX-1-IN-2/3-SAT, since most clauses will have size 2 and some will have size 3. However, we'll stick with the simpler name.

techniques can take us with respect to TSP (and also its variants, see for example [8]) may thus be an interesting question.

The main result of this paper is given below and it follows directly from the construction of section 4.1 and Lemmata 1,2.

Theorem 1. *For all $\epsilon > 0$ there is no polynomial-time $(\frac{92.3}{91.8} - \epsilon)$ -approximation algorithm for TSP, unless $P=NP$.*

2 Preliminaries

We will denote graphs by $G(V, E)$. All graphs are assumed to be undirected, loop-less and edge-weighted, meaning that there is also a function $w : E \rightarrow \mathbf{R}^+$. In some cases we will allow E to be a multi-set, that is, we may allow parallel edges. In the case of a multi-set E that contains several copies of some elements, when we write $\sum_{e \in E} w(e)$ we mean the sum that has one term for each copy. A (multi-)graph is Eulerian if there exists a closed walk that visits all its vertices and uses each edge once. It is well known that a (multi-)graph is Eulerian iff it is connected and all its vertices have even degree. We will use $[n]$ to denote the set $\{1, 2, \dots, n\}$. We will use $\mathbf{E}[X]$ to denote the expectation of a random variable X .

In the metric Traveling Salesman Problem (TSP) we are given as input an edge-weighted undirected graph $G(V, E)$. Let $d(u, v)$, for $u, v \in V$ denote the shortest-path distance from u, v . The objective is to find an ordering v_1, v_2, \dots, v_n of the vertices such that $\sum_{i=1}^{n-1} d(v_i, v_{i+1}) + d(v_n, v_1)$ is minimized.

Another, equivalent view of the TSP is the following: given an edge-weighted graph $G(V, E)$ we seek to find a multi-set E_T consisting of edges from E such that the graph induced by E_T spans V , is Eulerian and the sum of the weights of all edges in E_T is minimized. It is not hard to see that the two formulations are equivalent.

We generalize the Eulerian multi-graph formulation as follows: a multi-set E_T of edges from E is a quasi-tour iff the degrees of all vertices in the multi-graph $G_T(V, E_T)$ are even. The cost of a quasi-tour is defined as $\sum_{e \in E_T} w(e) + 2(c(G_T) - 1)$, where $c(G_T)$ denotes the number of connected components of the multi-graph. It is not hard to see that a TSP tour can also be considered a quasi-tour with the same cost, but in a weighted graph there could potentially be a quasi-tour that is cheaper than the optimal tour.

2.1 Forced edges

As mentioned, we will view TSP as the problem of selecting edges from E to form a minimum-weight multi-set E_T that makes the graph Eulerian. It is easy to see that no edge will be selected more than twice, since if an edge is selected three times we can remove two copies of it from E_T and the graph will still be Eulerian while we have improved the cost.

In our construction we would like to be able to stipulate that some edges are to be used at least once in any valid tour. We can achieve this with the following trick: suppose that there is an edge (u, v) with weight w that we want to force into every tour. We sub-divide this edge a large number of times, say $T - 1$, that is, we remove the edge and replace it with a path of T edges going through new vertices of degree two. We then redistribute the original edge's weight to the T newly formed edges, so that each has weight w/T . Now, any tour that fails to use two or more of the newly formed edges must be disconnected. Any tour that fails to use exactly one of them can be augmented by

adding two copies of the unused edge. This only increases the cost by $2w/T$, which can be made arbitrarily small by giving T an appropriately large value. Therefore, we may assume without loss of generality that in our construction we can force some edges to be used at least once. Note that these arguments apply also to quasi-tours.

3 Intermediate CSPs

In this section we will design and prove inapproximability for a family of instances of MAX-1-IN-3-SAT with some special structure. We will use these instances (and their structure) in the next section where we reduce from MAX-1-IN-3-SAT to TSP.

Let I_1 be a system of m linear equations mod 2, each consisting of exactly three variables. Let n be the total number of variables appearing in I_1 and let the variables be denoted as $x_i, i \in [n]$. Let B be the maximum number of times any variable appears. We will make use of the following seminal result due to Håstad:

Theorem 2 ([7]).

For all $\epsilon > 0$ there exists a B such that given an instance I_1 as above it is NP-hard to decide if there is an assignment that satisfies at least $(1 - \epsilon)m$ equations or all assignment satisfy at most $(\frac{1}{2} + \epsilon)m$ equations.

3.1 Bounded Occurrences

In I_1 each variable appears at most a constant number of times B , where B depends on ϵ . We would like to reduce the maximum number of occurrences of each variable to a small absolute constant. For this, one typically uses some kind of expander or amplifier construction. Here we will rely on a construction due to Berman and Karpinski that reduces the number of occurrences to 5.

Theorem 3 ([3]).

Consider the family of bipartite graphs $G(L, R, E)$, where $|L| = B, |R| = 0.8B$, all vertices of L have degree 4, all vertices of R have degree 5 and B is a sufficiently large multiple of 5. If we select uniformly at random a graph from this family then with high probability it has the following property: for any $S \subseteq L \cup R$ such that $|S \cap L| \leq \frac{|L|}{2}$ the number of edges in E with exactly one endpoint in S is at least $|S \cap L|$.

We now use the above construction to construct a system of equations where each variable appears exactly 5 times. First, we may assume that in I_1 the number of appearances of each variable is a multiple of 5 (otherwise, repeat all equations four times). Also, by repeating all the equations we can make sure that all variables appear at least B' times, where B' is a sufficiently large number to make Theorem 3 hold.

For each variable x_i in I_1 we introduce the variables $x_{(i,j)}, j \in [d(i)]$ and $y_{(i,j)}, j \in [0.8d(i)]$ where $d(i)$ is the number of appearances of x_i in the original instance. We call $X_i = \{x_{(i,j)} \mid j \in [d(i)]\} \cup \{y_{(i,j)} \mid j \in [0.8d(i)]\}$ the cloud that corresponds to x_i . Construct a bipartite graph with the property described in Theorem 3 with $L = [d(i)], R = [0.8d(i)]$ (since $d(i) < B$ is a constant that depends only on ϵ this can be done in constant time by brute force). For each edge $(j, k) \in E$ introduce the equation $x_{(i,j)} + y_{(i,k)} = 1$. Finally, for each equation $x_{i_1} + x_{i_2} + x_{i_3} = b$ in I_1 , where this is the j_1 -th appearance of x_{i_1} , the j_2 -th appearance of x_{i_2} and the j_3 -th appearance of x_{i_3} replace it with the equation $x_{(i_1,j_1)} + x_{(i_2,j_2)} + x_{(i_3,j_3)} = b$.

Denote this instance by I_2 and we have $|I_2| = 13m$, with $12m$ equations having size 2. A consistent assignment to a cloud X_i is an assignment that sets all $x_{(i,j)}$ to b and all $y_{(i,j)}$ to $1 - b$. By standard arguments using the graph of Theorem 3 we can show that an optimal assignment to I_2 is consistent (in each inconsistent cloud set S to be the vertices with the minority assignment; flipping all variables of S cannot make the solution worse). From this it follows that it is NP-hard to distinguish if the maximum number of satisfiable equations is at least $(13 - \epsilon)m$ or at most $(12.5 + \epsilon)m$.

3.2 MAX-1-IN-3-SAT

In the MAX-1-IN-3-SAT problem we are given a collection of clauses $(l_i \vee l_j \vee l_k)$, each consisting of at most three literals, where each literal is either a variable or its negation. A clause is satisfied by a truth assignment if exactly one of its literals is set to True. The problem is to find an assignment that satisfies the maximum number of clauses.

We would like to produce a MAX-1-IN-3-SAT instance from I_2 . Observe that it is easy to turn the size two equations $x_{(i,j)} + y_{(i,k)} = 1$ to the equivalent clauses $(x_{(i,j)} \vee y_{(i,k)})$. We only need to worry about the m equations of size three.

If the k -th size-three equation of I_2 is $x_{(i_1,j_1)} + x_{(i_2,j_2)} + x_{(i_3,j_3)} = 1$ we introduce three new auxilliary variables $a_{(k,i)}$, $i \in [3]$ and replace the equation with the three clauses $(x_{(i_1,j_1)} \vee a_{(k,1)} \vee a_{(k,2)})$, $(x_{(i_2,j_2)} \vee a_{(k,2)} \vee a_{(k,3)})$, $(x_{(i_3,j_3)} \vee a_{(k,1)} \vee a_{(k,3)})$. If the right-hand-side of the equation is 0 then we add the same three clauses except we negate $x_{(i_1,j_1)}$ in the first clause. We call these three clauses the cluster that corresponds to the k -th equation.

It is not hard to see that if we fix an assignment to $x_{(i_1,j_1)}, x_{(i_2,j_2)}, x_{(i_3,j_3)}$ that satisfies the k -th equation of I_2 then there exists an assignment to $a_{(k,1)}, a_{(k,2)}, a_{(k,3)}$ that satisfies the whole cluster. Otherwise, at most two of the clauses of the cluster can be satisfied. Furthermore, in this case there exist three different assignments to the auxilliary variables that satisfy two clauses and each leaves a different clause unsatisfied.

From now on, we will denote by M the set of (main) variables $x_{(i,j)}$, by C the set of (checker) variables $y_{(i,j)}$ and by A the set of (auxilliary) variables $a_{(k,i)}$. Call the instance of MAX-1-IN-3-SAT we have constructed I_3 . Note that it consists of $15m$ clauses and $8.4m$ variables.

4 TSP

4.1 Construction

We now describe a construction that encodes I_3 into a TSP instance $G(V, E)$. Rather than viewing this as a generic construction from MAX-1-IN-3-SAT to TSP, we will at times need to use facts that stem from the special structure of I_3 . In particular, the fact that variables can be partitioned into sets M, C, A , such that variables in $M \cup C$ appear five times and variables in A appear twice; the fact that most clauses have size two and they involve one positive variable from M and one positive variable from C ; and also the fact that clauses of size three come in clusters as described in the construction of I_3 .

As mentioned, we assume that in the graph $G(V, E)$ we may include some forced edges, that is, edges that have to be used at least once in any tour. The graph includes a central vertex, which we will call s . For each variable in $x \in M \cup C \cup A$ we introduce two new vertices named x^L and x^R , which we will call the left and right terminal associated with x . We add a forced edge

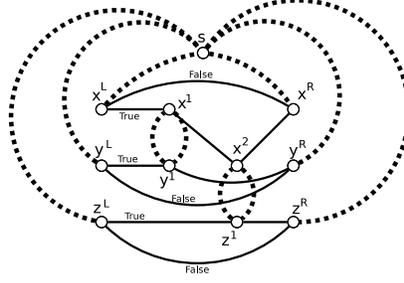


Fig. 1. Example construction for the clause $(x \vee y) \wedge (x \vee z)$. Forced edges are denoted by dashed lines. There are two terminals for each variable and two gadgets that represent the two clauses. The True edges incident on the terminals are re-routed through the gadgets where each variable appears positive. The False edges connect the terminals directly since no variable appears anywhere negated.

from each terminal to s . For terminals that correspond to variables in $M \cup C$ this edge has weight $7/4$, while for variables in A it has weight $1/2$. We also add two (parallel) non-forced edges between each pair of terminals, each having a weight of 1 (we will later break down at least one from each pair of these, so the graph we will obtain in the end will be simple). Informally, these two edges encode an assignment to each variable: we arbitrarily label one the True edge and the other the False edge, the idea being that a tour should pick exactly one of these for each variable and that will give us an assignment. We will re-route these edges through the clause gadgets as we introduce them, depending on whether each variable appears in a clause positive or negative.

Now, we add some gadgets to encode the size-two clauses of I_3 . Let $(x_{(i,j_1)} \vee y_{(i,j_2)})$ be a clause of I_3 and suppose that this is the k_1 -th clause that contains $x_{(i,j_1)}$ and the k_2 -th clause that contains $y_{(i,j_2)}$, $k_1, k_2 \in [5]$. Then we add two new vertices to the graph, call them $x_{(i,j_1)}^{k_1}$ and $y_{(i,j_2)}^{k_2}$. Add two forced edges between them, each of weight $3/2$ (recall that forced edges represent long paths, so these are not really parallel edges). Finally, re-route the True edges incident on $x_{(i,j_1)}^L$ and $y_{(i,j_2)}^L$ through $x_{(i,j_1)}^{k_1}$ and $y_{(i,j_2)}^{k_2}$ respectively. More precisely, if the True edge incident on $x_{(i,j_1)}^L$ connects it to some other vertex u , remove that edge from the graph and add an edge from $x_{(i,j_1)}^L$ to $x_{(i,j_1)}^{k_1}$ and an edge from $x_{(i,j_1)}^{k_1}$ to u . All these edges have weight one and are non-forced (see Figure 1).

We use a similar gadget for clauses of size three. Consider a cluster $(x_{(i_1,j_1)} \vee a_{(k,1)} \vee a_{(k,2)})$, $(x_{(i_2,j_2)} \vee a_{(k,2)} \vee a_{(k,3)})$, $(x_{(i_3,j_3)} \vee a_{(k,1)} \vee a_{(k,3)})$ and suppose for simplicity that this is the fifth appearance for all the main variables of the cluster. Then we add the new vertices $x_{(i_1,j_1)}^5, x_{(i_2,j_2)}^5, x_{(i_3,j_3)}^5$ and also the vertices $a_{(k,1)}^1, a_{(k,1)}^2, a_{(k,2)}^1, a_{(k,2)}^2$ and $a_{(k,3)}^1, a_{(k,3)}^2$. To encode the first clause we add two forced edges of weight $5/4$, one from $x_{(i_1,j_1)}^5$ to $a_{(k,1)}^1$ and one from $x_{(i_1,j_1)}^5$ to $a_{(k,2)}^1$. We also add a forced edge of weight 1 from $a_{(k,1)}^1$ to $a_{(k,2)}^1$, thus making a triangle with the forced edges (see Figure 2). We re-route the True edge from $a_{(k,1)}^L$ through $a_{(k,1)}^1$ and $a_{(k,2)}^1$. We do similarly for the other two auxiliary variables and the main variables. Finally, for a cluster where $x_{(i_1,j_1)}$ is negated, we use the same construction except that rather than re-routing the True edge that is incident on $x_{(i_1,j_1)}^L$ we re-route the False edge. This completes the construction.

4.2 From Assignment to Tour

Let us now prove one direction of the reduction and in the process also give some intuition about the construction. Call the graph we have constructed $G(V, E)$.

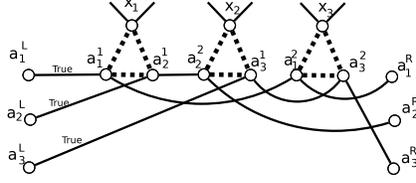


Fig. 2. Example construction fragment for the cluster $(x_1 \vee a_1 \vee a_2) \wedge (x_2 \vee a_2 \vee a_3) \wedge (x_3 \vee a_1 \vee a_3)$. The False edges which connect each pair of terminals and the forced edges that connect terminals to s are not shown.

Lemma 1. *If there exists an assignment to the variables of I_3 that leaves at most k equations unsatisfied, then there is a tour of G with cost at most $T = L + k$, where $L = 91.8m$.*

Proof. Observe that by construction we may assume that all the unsatisfied clauses of I_3 are in the clusters and that at most one clause in each cluster is unsatisfied, otherwise we can obtain a better assignment. Also, if an unsatisfied clause has all literals set to False we can flip the value of one of the auxilliary variables without increasing the number of violated clauses. Thus, we may assume that all clauses have a True literal. Also, we may assume that no clause has all literals set to True: suppose that a clause does, then both auxilliary variables of the clause are True. We set them both to False, gaining one clause. If this causes the two other clauses of the cluster to become unsatisfied, set the remaining auxilliary variable to True. We conclude that all clauses have either one or two True literals.

Our tour uses all forced edges exactly once. For each variable x set to True in the assignment the tour selects the True edge incident on the terminal corresponding to x . If the edge has been re-routed all its pieces are selected, so that we have selected edges that make up a path from x^L to x^R . Otherwise, if x is set to False in the assignment the tour selects the corresponding False path.

Observe that this is a valid quasi-tour because all vertices have even degree (for each terminal we have selected the forced edge plus one more edge, for gadget vertices we have selected the two forced edges and possibly the two edges through which True or False was re-routed). Also, observe that the tour must be connected, because each clause contains a True literal, therefore for each gadget two of its external edges have been selected and they are part of a path that leads to the terminals.

The cost of the tour is at most $F + N + M + k$, where F is the total cost of all forced edges in the graph and N, M are the total number of variables and clauses respectively in I_3 . To see this, notice that there are $2N$ terminals, and there is one edge incident on each and there are M clause gadgets, $M - k$ of which have two selected edges incident on them and k of which have four. Summing up, this gives $2N + 2M + 2k$, but then each unit-weight edge has been counted twice, meaning that the non-forced edges have a total cost of $N + M + k$.

Finally, we have $N = 8.4m$, $M = 15m$ and $F = 3 \times 12m + \frac{7}{2} \times 3m + \frac{7}{2} \times 5.4m + 1 \times 3m = 68.4m$, where the terms are respectively the cost of size-two clause gadgets, the cost of size-three clause gadgets, the cost of edges connecting terminals to s for the main variables and for the auxilliary variables. We have $F + N + M = 91.8m$. \square

4.3 From Tour to Assignment

We would like now to prove the converse of Lemma 1, namely that if a tour of cost $L + k$ exists then we can find an assignment that leaves at most k clauses unsatisfied. Because this is the more

interesting part of the proof, let us first give some high-level intuition and in the process justify the weights we have selected in our construction.

Informally, we could start from a simple base case: suppose that we have a tour such that all edges of G are used at most once. It is not hard to see that this then corresponds to an assignment, as in the proof of Lemma 1. So, the problem is how to avoid tours that may use some edges twice.

To this end, we first give some local improvement arguments that make sure that the number of problematic edges, which are used twice, is limited. However, arguments like these can only take us so far, and we would like to avoid having too much case analysis.

We therefore try to isolate the problem. For variables in $M \cup C$ which the tour treats honestly, that is, variables which are not involved with edges used twice, we directly obtain an assignment from the tour. For the other variables in $M \cup C$ we pick a random value and then extend the whole assignment to A in an optimal way. We want to show that the expected number of unsatisfied clauses is at most k .

The first point here is that if a clause containing only honest variables turns out to be violated, the tour must also be paying an extra cost for it. The difficulty is therefore concentrated on clauses with dishonest variables.

By using some edges twice the tour is paying some cost on top of what is accounted for in L . We would like to show that this extra cost is larger than the number of clauses violated by the assignment. It is helpful to think here that it is sufficient to show that the tour pays an additional cost of $\frac{5}{2}$ for each dishonest variable, since main variables appear 5 times.

A crucial point now is that, by a simple parity argument, there has to be an even number of violations (that is, edges used twice) for each variable (Lemma 4). This explains the weights we have picked for the forced edges in size-three gadgets ($\frac{5}{4}$) and for edges connecting terminals to s ($\frac{7}{4} = \frac{5}{4} + \frac{1}{2}$ or $\frac{5}{4}$ extra to the cost already included in L for fixing the parity of the terminal vertex). Two such violations give enough extra cost to pay for the expected number of unsatisfied clauses containing the variable.

At this point, we could also set the weights of forced edges in size-two gadgets to $\frac{5}{2}$, which would be split among the two dishonest variables giving $\frac{5}{4}$ to each. Then, any two violations would have enough additional cost to pay for the expected unsatisfied clauses. However, we are slightly more careful here: rather than setting all dishonest variables in $M \cup C$ independently at random, we pick a random but consistent assignment for each cloud. This ensures that all size-two clauses with violations will be satisfied. Thus, it is sufficient for violations in them to have a cost of $\frac{3}{2}$: the amount "paid" to each variable is now $\frac{3}{4} = \frac{5}{4} - \frac{1}{2}$, but the expected number of unsatisfied clauses with this variable is also decreased by $\frac{1}{2}$ since one clause is surely satisfied.

Let us now proceed to give the full details of the proof. Recall that if a tour of a certain cost exists, then there exists also a quasi-tour of the same cost. It suffices then to prove the following:

Lemma 2. *If there exists a quasi-tour of G with cost at most $L + k$ then there exists an assignment to the variables of I_3 that leaves at most k clauses unsatisfied.*

Before moving on to the proof of Lemma 2 let us make some easy observations. First, observe that if a quasi-tour uses a unit-weight edge twice then we can remove both of these appearances of the edge from the solution without increasing the cost, since the number of components can only increase by one. Therefore, all (non-forced) edges of weight one are used at most once.

Second, if both forced edges of a gadget of size two are used twice then we can remove one appearance of each from the solution, decreasing the cost. Similarly, in a gadget of size three if two

forced edges are used twice then we can drop one copy of each and use the third edge twice, making the tour cheaper. Therefore, in each gadget there is at most one forced edge that is used twice.

Third, if both forced edges that connect the terminals x^L, x^R to s are used twice, then we can remove one appearance of each from the solution and replace them by the shortest path from x^L to x^R that uses only non-forced unit weight edges. This has weight at most one for the auxilliary variables and two for the rest, which in both cases is at most as much as the weight of the removed edges.

Given a tour E_T , we will say that a variable x is honestly traversed in that tour if all the forced edges that involve it are used exactly once (this includes the forced edges incident on x^L, x^R and $x^i, i \in [5]$).

Let us prove two more useful facts.

Lemma 3. *There exists an optimal tour where all forced edges between two different vertices that correspond to two variables in A are used exactly once.*

Proof. We refer the reader again to Figure 2. Suppose for contradiction that the edge (a_1^1, a_2^1) is used twice (the other cases are equivalent by symmetry since all vertices a_i^j are connected to one terminal and one other such vertex).

First, suppose that at least one of the edges that connect one of these two endpoints to a terminal is selected, say the edge (a_1^L, a_1^1) . Then modify the solution by removing that edge and a copy of the duplicate forced edge and adding a copy of (a_2^L, a_2^1) , (s, a_2^L) and (s, a_1^L) . This does not increase the cost.

Second, suppose that both (s, a_1^L) and (s, a_2^L) are used twice in the tour. Then we can modify the tour by dropping one copy of each and a copy of the duplicate gadget edge and adding (a_1^L, a_1^1) and (a_2^L, a_2^1) .

Finally, suppose that none of the previous two cases is true. Thus, neither of (a_1^L, a_1^1) , (a_2^L, a_2^1) is used in the tour. This means that (a_1^1, a_1^2) and (a_2^1, a_2^2) are both used to ensure that a_1^1, a_2^1 have even degree. Also, one of the edges connecting a terminal to s is used once, say (s, a_1^L) . This means that the False edge incident to a_1^L must be used to make the degree of a_1^L even. Remove the False edge and the edge (a_1^1, a_2^1) from the tour and add the edges (a_1^L, a_1^1) and (a_1^R, a_2^1) . This reduces to the first case. \square

Lemma 4. *In an optimal tour, if a variable is dishonest then it must be dishonest twice. More precisely, the number of forced edges that involve the variable (either inside gadgets or connecting terminals to s) and are used twice must be even.*

Proof. Consider a variable x and first suppose that neither of the forced edges connecting s to the terminals is used twice, but there is a single forced edge in a gadget that is used twice. It follows that the vertex that corresponds to x in that gadget has an odd number of unit-weight edges incident to it selected. The two terminals have a single selected unit-weight edge incident on them and all other vertices that belong to x have an even number of incident unit-weight edges selected, since their total degree is even. Thus, summing the number of selected unit-weight edges incident on all the vertices that belong to x we get an odd number, which is a contradiction since we counted each such edge exactly twice. A similar argument applies if one assumes that one of the forced edges incident on the terminals is used twice and all other forced edges are used once. \square

Observe that it follows from Lemmata 3,4 that if all the main variables involved in a cluster are honest then the auxilliary variables of that cluster are also honest. This holds because if the main

variables are honest then by Lemma 3 no forced edge inside the gadgets of the cluster is used twice, so by Lemma 4 and the fact that at least one of the forced edges incident on the terminals is used once, the auxilliary variables are honest.

We would like now to be able to extract a good assignment even if a tour is not honest, thus indirectly proving that honest tours are optimal.

Proof (Lemma 2).

Consider the following algorithm to extract an assignment from the tour: first, for each variable in $M \cup C$ that was traversed honestly give it the same truth-value as in the tour, that is, if the tour selects the True edge incident on the corresponding terminal, set the variable to True, otherwise to False. To decide on the value of the dishonest variables from $M \cup C$ produce n random bits $b_i, i \in [n]$ (recall that n is the number of variables of I_1 , or the number of clouds in I_3). For each i set all dishonest variables $x_{(i,j)}$ to be equal to b_i and all dishonest $y_{(i,j)}$ to be equal to $1 - b_i$. This ensures that size-two clauses that contain two dishonest variables are always satisfied, since these clauses are always between two variables of the same cloud.

Let us also assign the auxilliary variables. If there is an assignment to the auxilliary variables of a cluster that satisfies all three clauses select it. Otherwise, select an assignment that violates the clause of a dishonest variable from M , if such a variable exists, and satisfies the other two. If all main variables are honest, as we have argued the auxilliary variables are also honest, so pick the corresponding assignment.

We now have a randomized assignment for I_3 , so let us upper-bound the expected number of unsatisfied clauses. Let U be a random variable equal to the set of unsatisfied clauses and let $U = U_1 \cup U_2$ where U_1 contains all the unsatisfied clauses that involve only honest variables from $M \cup C$ and U_2 the rest. (Note that U_1 is not random.)

The cost of the quasi-tour we have is $T \leq F + N + M + k$. Let E_G be the set of forced gadget edges that the tour uses twice. Let E_S be the set of forced edges incident on s that the tour uses twice. Let E_1 be the set of unit-weight edges that the tour uses (recall that each is used once). Let U'_1 be the set of clauses that correspond to gadgets the tour visits at least twice (meaning they have at least four incident edges selected). Let U''_1 be the set of clauses that correspond to gadgets the tour does not visit (meaning that each forms its own connected component).

We have $T = \sum_{e \in E_T} w(e) + 2(c(G_T) - 1) = F + \sum_{e \in E_1} w(e) + \sum_{e \in E_G} w(e) + \sum_{e \in E_S} w(e) + 2(c(G_T) - 1)$.

By definition $\sum_{e \in E_1} w(e) = |E_1|$. Let us try to lower-bound this quantity using arguments similar to the proof of Lemma 1. After the selection of the forced edges there are $2N - |E_S|$ terminals with odd degree, so each has a selected unit-weight edge incident to it. There are $|U'_1|$ gadgets with at least four selected incident edges and $M - |U'_1| - |U''_1|$ gadgets with two selected incident edges. Summing up we get $2N - |E_S| + 2M + 2|U'_1| - 2|U''_1|$, but each edge is counted twice, so we have $|E_1| \geq N - \frac{1}{2}|E_S| + M + |U'_1| - |U''_1|$.

Using this fact we get $T \geq F + N + M + \sum_{e \in E_G} w(e) + \sum_{e \in E_S} (w(e) - \frac{1}{2}) + |U'_1| + 2(c(G_T) - 1) - |U''_1|$.

Now, observe that $|U''_1| \leq c(G_T) - 1$, because each element of U''_1 forms a component and there is one component that is not an element of U''_1 (the one that contains s). Thus, $2(c(G_T) - 1) - |U''_1| \geq |U'_1|$. Combining this with the above we get $T \geq F + N + M + \sum_{e \in E_G} w(e) + \sum_{e \in E_S} (w(e) - \frac{1}{2}) + |U'_1| + |U''_1|$. Given the known upper-bound on the cost of the tour we have that $k \geq \sum_{e \in E_G} w(e) + \sum_{e \in E_S} (w(e) - \frac{1}{2}) + |U'_1| + |U''_1|$.

We now need to argue two facts and we are done. First $|U_1| \leq |U'_1| + |U''_1|$. Recall that U_1 is the set of unsatisfied clauses that involve honest variables. Since the variables are traversed honestly

their corresponding gadgets are either visited at least twice or not at all, so they are counted in $|U_1|$ or in $|U_1''|$.

Second, we would like to show that $\mathbf{E}[|U_2|] \leq \sum_{e \in E_G} w(e) + \sum_{e \in E_S} (w(e) - \frac{1}{2})$. Before we do that, observe that if we show this then it follows that $\mathbf{E}[|U|] = \mathbf{E}[|U_2|] + |U_1| \leq k$, so there must exist an assignment that leaves no more than k clauses unsatisfied and we are done.

So, let us try to upper-bound $\mathbf{E}[|U_2|]$, which is the expected number of unsatisfied clauses that contain a dishonest variable. First, observe that if there are dishonest auxiliary variables in a cluster by the construction of the assignment we have ensured that any unsatisfied clause must contain a dishonest main variable. Therefore, it suffices to count the expected number of unsatisfied clauses that contain a dishonest main variable.

Let us define a credit $cr(x)$ for each dishonest main variable x . If a forced edge connecting a terminal to s is used twice we give x a credit of $5/4$ (which is equal to $w(e) - \frac{1}{2}$, since these edges have weight $\frac{7}{4}$). If a forced edge in a gadget that involves x and another main variable is used twice we give x a credit of $\frac{3}{4}$ (which is equal to $w(e)/2$). Finally, if a forced edge in a gadget that involves x and an auxiliary variable is used twice we give x a credit of $\frac{5}{4}$ (which is equal to $w(e)$). We define $cr(x)$ to be the sum of credits given to x in this process.

If D is the set of dishonest main variables then it is not hard to see that $\sum_{x \in D} cr(x) \leq \sum_{e \in E_G} w(e) + \sum_{e \in E_S} (w(e) - \frac{1}{2})$. All edges are counted once in the sum of credits, except for those from E_G that involve two main variables, for which each is credited half the weight.

We will now argue that the expected number of unsatisfied clauses that contain a variable x is at most $cr(x)$. Recall that clauses containing x and another dishonest main variable are by construction satisfied, while clauses made up of x and one honest variable are satisfied with probability $1/2$. Also, clauses of size 3 that contain x are satisfied with probability at least $1/2$, since with probability $1/2$ the equation from which the cluster was obtained is satisfied. Thus, if $cr(x) \geq \frac{5}{2}$ we are done. We know that x received at least two credits by Lemma 4, so $cr(x) \geq \frac{3}{2}$, as the smallest credit is $\frac{3}{4}$. If $cr(x) = \frac{3}{2}$ then x must have received two credits that were shared with other dishonest variables. Therefore, there are two clauses containing x which are surely satisfied, and out of the other three the expected number of unsatisfied clauses is $\frac{3}{2} \leq cr(x)$. Similarly, if $cr(x) = 2$, then x shared a credit with another variable at least once, so one clause is surely satisfied and the expected number of unsatisfied clauses out of the other four is 2.

We therefore have $\mathbf{E}[|U_2|] \leq \sum_{x \in D} cr(x) \leq \sum_{e \in E_G} w(e) + \sum_{e \in E_S} (w(e) - \frac{1}{2})$ and this concludes the proof. \square

5 Conclusions

We have given an alternative and (we believe) simpler inapproximability proof for TSP, also modestly improving the known bound. We believe that the approach followed here where the hardness proof goes explicitly through bounded occurrence CSPs is more promising than the somewhat ad-hoc method of [13], not only because it is easier to understand but also because we stand to gain almost "automatically" from improvements in our understanding of the inapproximability of bounded occurrence CSPs. In particular, though we used the 5-regular amplifiers from [3], any such amplifier would work essentially "out of the box", and any improved construction could imply an improvement in our bound. Nevertheless, the distance between the upper and lower bounds on the approximability of TSP remains quite large and it seems that some major new idea will be needed to close it.

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