

Assignment 1 - Homework Exercises on Approximation Algorithms

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September 22, 2015

A.I-1

We will show that the approximation ratio of the *GreedySchedulingAlgorithm* is at least $2 - \frac{1}{m}$ by showing an example as follow.

Let's consider this setting:

- 3 machines: M1, M2, M3
- 7 jobs: 1, 1, 1, 1, 1, 1, 3

GreedySchedulingAlgorithm will come up with this scheduling:

- M1: 1 1 3
- M2: 1 1
- M3: 1 1

Thus $ALG = makespan = 1 + 1 + 3 = 5$

We know that:

$$OPT \geq \max(Average_{load}, \max(tj)) \quad (1)$$

Where

$$Average_{load} = \frac{1}{m} \sum_{i=1}^n j_i = \frac{9}{3} = 3$$

And

$$\max(t_j) = 3$$

Here we can find a solution with $makespan = 3$. That is:

- M1: 3
- M2: 1 1 1
- M3: 1 1 1

Therefore, $OPT = 3$

Thus, the approximation ratio is:

$$\rho = \frac{ALG}{OPT} = \frac{5}{3} \quad (2)$$

According to the theorem, the estimated ratio is:

$$\rho_{estimated} = 2 - \frac{1}{m} = 2 - \frac{1}{3} = \frac{5}{3} \quad (3)$$

From 2 and 3, we have $\rho_{estimated} = \rho$. Therefore, this bound is tight.

A.I-2

From the question, we know that

$$\begin{aligned} m &= 10 \\ \sum_{j=1}^n t_j &\geq 1000 \\ t_j &\in [1, 20] ; \text{ for all } i \leq j \leq n \end{aligned}$$

Let T'_{i^*} denote the load of M_i before t_j^* , last job, is assigned to the machine. Thus T_i^* , which represents makespan of the assignment, equals to

$$T_i^* = T'_{i^*} + t_j^*$$

Because T'_{i^*} is the minimum load among all machines, so that we can derive

$$T'_{i^*} \leq \frac{1}{m} \sum_{i=1}^m T'_i = \sum_{j=1}^{j^*} t_j \leq \frac{1}{m} \left[\sum_{j=1}^n t_j - t_j^* \right] \leq LB$$

Then we can derive

$$\begin{aligned} T_i^* &= T'_{i^*} + t_j^* \\ &\leq \frac{1}{m} \left[\sum_{j=1}^n t_j - t_j^* \right] + t_j^* \\ &\leq \frac{1}{m} \sum_{j=1}^n t_j + \left(1 - \frac{1}{m}\right) t_j^* \\ &\leq 100 + \left(1 - \frac{1}{10}\right) 20 \\ &\leq 118 \end{aligned}$$

According *Algorithm Greedy Scheduling* and the question, we know

$$\begin{aligned} \max \left(\frac{1}{m} \sum_{j=1}^n t_j, \max_{1 \leq j \leq n} (t_j) \right) &\leq LB \leq OPT \\ \max_{1 \leq j \leq n} (t_j) &= 20 \end{aligned}$$

Then we can derive

$$\max \left(\frac{1}{m} \sum_{j=1}^n t_j, 20 \right) \leq LB$$

Since $\frac{1}{m} \sum_{j=1}^n t_j \geq 1000$, thus

$$\begin{aligned} 100 &\leq LB \\ &\leq OPT \end{aligned}$$

Therefore, $\text{approximation-ratio}(\rho)$ equals to

$$\begin{aligned} T_i^* &\leq \rho OPT \\ \frac{118}{100} &\leq \rho \\ 1.18 &\leq \rho \end{aligned}$$

For this particular setting, *Algorithm Greedy Scheduling* is 1.18 approximation algorithm.

A.I-3

(i)

Assume we have the optimal solution, which has n squares. That is:

$$n \leq LB \leq OPT$$

Now we put our set of points into a grid with unit-size cells. Each unit square can overlap at most 4 cells in such a grid, then our optimal solution can be split into at most $4n$ squares. Therefore,

$$ALG \leq 4n = 4.OPT$$

So this algorithm is 4-approximation.

(ii)

We propose the algorithm as follow.

This algorithm is correct because:

- Every point in p will be covered by a square
- There are no intersections between the squares because we traverse in one direction

This algorithm consists of 2 parts: QuickSort and Traversing the Point to create squares. Let t be the run time of this algorithm, $t_{quicksort}$ be the time for quick-sort, and t_{assign} be the time for creating the squares. We have:

$$t = t_{quicksort} + t_{assign} \leq n \log n + n = O(n \log n) \quad (4)$$

Thus the runtime of this algorithm is $O(n \log n)$.

Algorithm 1 Finding minimum row square cover

Require: Set of Points P **Ensure:** Min Square Cover min **Operation:**

```
set  $currentCoveringPosition = -1$ 
QuickSortAscending( $S$ )
for all Point  $p$  in  $P$  do
    if  $p.x > currentCoveringPosition$  then
        create square  $s = (p.x, 1, p.x + 1, 0)$ ;
        add  $s$  to  $S$ 
        set  $currentCoveringPosition = p.x + 1$ 
    end if
set  $min = sizeof S$ 
return  $min$ 
end for
```

(iii)

The idea of our algorithm is that, we put all the points in to a coordinate system, then we divide the coordinate system into a set of unit rows (i.e. rows with height 1). For each row, we use algorithm 1 to find the minimum size square-cover. The global min-square-cover is the sum of all row-square-cover.

Algorithm 2 Finding global minimum square cover

Input: Set of points P **Output:** Min Square Cover min **Operation:**

```
currentMin = 0;
for all Row  $r$  in the space do
    currentMin += FindRowMinSquare()
end for
set  $min = currentMin$ 
return  $min$ 
```

Theorem. FindingGlobalMinimumSC is 2 – approximation

Proof. We prove this Theorem by induction.

If the optimal solution consists of only 1 square, then $OPT_1 = 1$. After applying our algorithm, the square can be split into at most 2 squares.

This is true because if the algorithm returns more than 2 squares, then there is a row which consists of more than 1 square. It means the margin of our points is larger than 1, then the optimal must have more than 1 squares to fit them. It contradicts with our assumption that $OPT_1 = 1$.

So $ALG_1 \leq 2 = 2OPT_1$

Suppose when $n = k$, the algorithm is true, that is $ALG_k \leq 2OPT_k$

Now we add some additional points which insert another square into the optimal solution. Now $n = k + 1$.

We have $OPT_{k+1} = OPT_k + 1$

Applying our algorithm, the final result is the sum of the original input ($n = k$) and the new input ($n = 1$). We know that the Theorem holds for both of them. We have:

$$\begin{aligned} ALG_{k+1} &= ALG_k + ALG_1 \\ &\leq 2OPT_k + 2 \\ &= 2(OPT_k + 1) \\ &= 2OPT_{k+1} \end{aligned}$$

Thus the Theorem also holds for $n = k + 1$. Therefore, it holds for all values of n .

In conclusion, this algorithm is 2 - *approximation*.

□

AII.1

(i)

We prove this statement by contradiction.

- Suppose that $V \setminus C$ is not an independent set of G . Then there exists a pair of vertices (u, v) in $V \setminus C$ which are connected by an edge $e \in E$. Thus, both u and v are not in C . Therefore, C is not the vertex cover of G anymore.

- Suppose C is not the vertex cover of G , then there exists a pair of vertices (u, v) that are connected by an edge $e \in E$ but are not in C . Thus, $u \in (V \setminus C)$ and $v \in (V \setminus C)$. Therefore, $(V \setminus C)$ is not the vertex cover of G anymore.

From the reasoning above, we can state that: C is the vertex cover of G if and only if $V \setminus C$ is an independent set of G .

(ii)

We prove that *ApproxMaxIndependentSet* is not a 2-approximation algorithm by showing a counter example. That is, consider a complete graph, for example, a graph $G = (V, E)$ where $V = x_1, x_2$ and $E = (x_1, x_2)$.

Applying the *ApproxMinVertexCover*(G), we get $C = x_1, x_2$ (picking both vertices from the edge).

Now we take the approx max independent set $ALG = V \setminus C = \emptyset$.

The optimal solution now is $OPT = 1$ (picking x_1 or x_2).

The approximation ratio is $\rho = \frac{OPT}{ALG} = \infty \neq 2$.

So the approximation ratio is not 2.

AII.2

(i)

The best possible scenario in the presented case is similar to following:

$$(x_1 \vee x_2 \vee x_3) \wedge (x_1 \vee x_4 \vee x_5) \wedge (x_1 \vee x_6 \vee x_7)$$

It can be seen that in this case x_1 is present in all the clauses of the CNF therefore we can eliminate all the clauses of the equation in the first run. This gives us a following lower bound:

$$LB = 1$$

We deduce then:

$$OPT \geq 1$$

We define approximation ratio ρ as:

$$\rho = \frac{ALG}{OPT}$$

Since we do not know if duplication of elements in a clause is allowed or not we will examine two possible scenarios.

Duplication allowed:

Consider the case when:

$$(x_1 \vee x_2 \vee x_2) \wedge (x_1 \vee x_3 \vee x_3) \wedge (x_1 \vee x_4 \vee x_4) \wedge \dots \wedge (x_1 \vee x_n \vee x_n)$$

We choose in each iteration elements unique for the clause like $x_2, x_3, x_4, \dots, x_n$. So we end up having chosen $n - 1$ elements, excluding the one that was common in all the clauses. That gives us:

$$\begin{aligned} ALG &= (n - 1) \\ \rho &= (n - 1) \end{aligned}$$

Duplication disallowed:

If duplication is not allowed as in the following CNF:

$$(x_1 \vee x_2 \vee x_3) \wedge (x_1 \vee x_2 \vee x_4) \wedge (x_1 \vee x_2 \vee x_5) \wedge \dots \wedge (x_1 \vee x_2 \vee x_n)$$

We can see that the algorithm chooses $n - 2$ resulting in :

$$\begin{aligned} ALG &= (n - 2) \\ \rho &= (n - 2) \end{aligned}$$

(ii)

For the algorithm to become a 3-approximation algorithm it should be modified so that in each iteration it chooses all three elements in a clause and eliminate all the clauses in CNF that contain any of these three elements.

Proof

Let D^* be a subset of D that only contains clauses that do not share any variable.

The optimal solution to the problem OPT contains at least one variable from each clause in D^* therefore :

$$OPT \geq |D^*|$$

In our algorithm after the modification, we select three variables in each clause in D^* , because there are no clauses that share common variables with them. The other clauses which have common variables as any clause in D^* are deleted. Thus:

$$\begin{aligned} ALG &= 3|D^*| \\ &\leq 3OPT \end{aligned}$$

Therefore it is a 3-approximation algorithm.

AII.3

(i)

Suppose a d -hypergraph $G = (V, E)$ which every edge $e \in E$ is incident to d vertices in V . To formulate 0/1 linear programming, we introduce $X = \{ x_1, x_2, \dots, x_n \}$ which x_i represents $v_i \in V$ in a linear programming. If $x_i = 1$, it means we pick v_i to the set of double vertex cover, $C \subset V$, and otherwise $x_i = 0$. For this solution, we want to find a minimum double vertex cover which requires at least 2 vertices from each edge are in C . Then, we can derive a constraint for 0/1 linear programming

$$\sum_{v_i \in e} x_i \geq 2 \text{ for all } e \in E ; \text{ at least 2 vertices are selected.}$$

Thus, we then formulate the linear programming.

$$\begin{array}{ll}
\text{Minimize} & \sum_{i=1}^n x_i \\
\text{Subject to} & \\
& \sum_{v_i \in e} x_i \geq 2 \quad \text{for all } e \in E \\
& x_i = \{0,1\} \quad \text{for all } x_i \in X
\end{array}$$

(ii)

Because we can not solve 0/1 linear program in polynomial time, what we have to do next is to relax the program to be a normal linear program by replacing $\{0,1\}$ constraint with $0 \leq x \leq 1$

Thus, the linear program is

$$\begin{array}{ll}
\text{Minimize} & \sum_{i=1}^n x_i \\
\text{Subject to} & \\
& \sum_{v_i \in e} x_i \geq 2 \quad \text{for all } e \in E \\
& 0 \leq x_i \leq 1 \quad \text{for all } x_i \in X
\end{array}$$

Let τ denote the rounding threshold such that

$$x_i = \begin{cases} 1, & \text{if } x_i \geq \tau \\ 0, & \text{otherwise} \end{cases}$$

The next step is to derive τ such that all constraints are satisfied and the algorithm always return a valid solution. Let denote x^* to be an ideal value

Algorithm 3 Finding double vertex cover

Input: V, E

Output: A minimum double vertex cover

Operation:

Solve the relaxed linear program corresponding to the given problem.

$$\text{Minimize} \quad \sum_{i=1}^n x_i$$

Subject to

$$\sum_{v_i \in e} x_i \geq 2 \text{ for all } e \in E$$

$$0 \leq x_i \leq 1 \text{ for all } x_i \in X$$

$$C \leftarrow \{ v_i \in V : x_i \geq \tau \}$$

return C

of any x_i such that it satisfies all constraints.

$$\begin{aligned} \sum_{x_i \in e} x_i &\geq 2 \forall e \in E \\ \sum_{i=1}^d x_i &\geq 2 \\ x_1 + \sum_{i=1}^{d-1} x_i &\geq 2 \end{aligned}$$

We would like to find a threshold τ that is small enough so that at least 2 vertices are selected. The extreme case is when $x_1 = 1$, then we have:

$$\begin{aligned} 1 + \sum_{i=1}^{d-1} x_i &\geq 2 \\ (d-1)x_i &\geq 1 \\ x_i &\geq \frac{1}{d-1} \\ \therefore \tau &= \frac{1}{d-1} \end{aligned}$$

Let W denote the value of an optimal to the relaxed linear program and OPT denote the minimum number of double vertex cover. Then $OPT \geq W$.

Now we can derive,

$$\begin{aligned}
|C| &= \sum_{v_i \in C} 1 \\
&\leq \sum_{v_i \in C} (d-1)x_i \\
&\leq (d-1) \sum_{v_i \in C} x_i \\
&\leq (d-1)W \\
&\leq (d-1)OPT
\end{aligned}$$

(iii)

Lets take an example of a complete 3-hypergraph, where the optimal double vertex cover is $|V| - 1$ to make sure every edge has at least 2 vertices selected. So the result of the 0/1-LP is $|V| - 1$.

The relaxed-LP formulation is as follow:

- Miminize $\sum_{i=1}^n x_i$
- Subject to: $\sum_{x_j \in e} x_j \geq 2$ for all edge e AND $0 \leq x_i \leq 1$

We run the algorithm by performing that relaxed-LP on the complete 3-hypergraph, and then round the result following the condition $x \geq \frac{1}{2}$.

For the complete 3-hypergraph, the relaxed-LP will return $x_i = \frac{2}{3}$ for all i so that each sum of vertices in an edge is 2.

Then the algorithm will pick all of the vertices because they satisfy the condition. The result is:

$$ALG = \frac{2}{3}|V|$$

The integrality gap, denoted by IG , is:

$$\begin{aligned}
IG &= \frac{|V| - 1}{\frac{2|V|}{3}} \\
&= \frac{3}{2} - \frac{3}{2|V|}
\end{aligned}$$

A.III-1

(i)

Let $T = \sum_{j=1}^n t_j$ be the total time of all the jobs. Since we define large job as having time $t \geq \epsilon T$, the maximum number of large jobs is:

$$n_{max} = \frac{T}{\epsilon T} = \frac{1}{\epsilon}$$

For each large job, there are two possible ways of assigning it to a machine. Therefore the possible ways that $\frac{1}{\epsilon}$ jobs can be scheduled into 2 machine is:

$$NumberOfWays = 2^{\frac{1}{\epsilon}}$$

Since machine 1 and machine 2 are identical (e.g. $0 - n$ and $n - 0$ are equal), we remove the duplicates leaving the total number of schedules at :

$$\begin{aligned} NumberOfWays &= \frac{2^{\frac{1}{\epsilon}}}{2} \\ &= 2^{\frac{1}{\epsilon}-1} \end{aligned}$$

(ii)

We have

$$OPT \geq \max\left(\frac{T}{2}, t_{max}\right)$$

where t_{max} is the maximum job size.

To obtain PTAS, We split the jobs up into two types :

$$\text{Job is } \begin{cases} \text{Large if } t_j \geq \epsilon T \\ \text{Small otherwise} \end{cases}$$

The PTAS algorithm runs as follow.

Algorithm 4 Load Balancing PTAS

Require: Set J of n jobs with running time t_j , ϵ

Ensure: Minimum max(makespan) between two machines.

Operation:

Define set of large jobs L where $t_j \geq \epsilon T \forall t_j \in L$

Define set of small jobs $S := J \setminus L$

List all possible combinations of $t_j \in L$ into 2 machines

Select the combination that has the lowest max(makespan)

for all t_j in S **do**

 Schedule t_j to the machine which has the lower current makespan

end for

return The max(makespan) between 2 machines

Proof

Let denote:

- ALG as a makespan generated by our solution
- T' as the makespan in the selected machine before assigning the last job
- t_{last} as the size of the last scheduled job

We come up with:

$$\begin{aligned} ALG &= T' + t_{last} \\ &\leq \frac{T - t_{last}}{2} + t_{last} \\ &\leq \frac{T}{2} + \frac{\epsilon T}{2} \\ &\leq (1 + \epsilon) \frac{T}{2} \\ &\leq (1 + \epsilon) LB \\ &\leq (1 + \epsilon) OPT \end{aligned}$$

When ϵ is small enough, ALG will return OPT solution due to the brute-force approach for large jobs. Then the approximation ratio still holds as $(1 + \epsilon)$ where ϵ is very small ($\epsilon \rightarrow 0$).

Running Time Since there can be only at most $2^{\frac{1}{\epsilon}-1}$ possible large jobs, then the brute-force part of the algorithm will have a running time of $O(2^{\frac{1}{\epsilon}-1})$. The greedy scheduling of the large jobs is faster with linear time $O(n)$ for n jobs. Leaving a total running time - $O(2^{\frac{1}{\epsilon}-1} + n)$, which is polynomial in term of n . So this algorithm satisfies the condition of a PTAS.

AIII.2

(i)

Let d denote the distance between 2 arbitrary vertices corresponding to P and d^* denote the distance after rounding $p_{i,x}, p_{i,y}$ where $p_{i,x}$ and $p_{i,y}$ denote the x- and y-coordinate of $p_i \in P$, by Δ .

$$d = \sqrt{(p_{i,x} - p_{j,x})^2 + (p_{i,y} - p_{j,y})^2}$$

$$d^* = \sqrt{(p_{i,x^*} - p_{j,x^*})^2 + (p_{i,y^*} - p_{j,y^*})^2}$$

We know that the range of p_x^* is

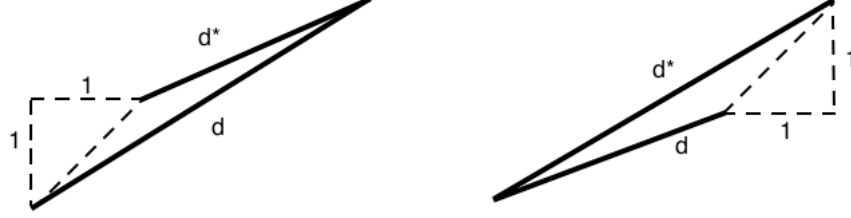
$$\frac{px}{\Delta} \leq p_x^* \leq \frac{px}{\Delta} + 1$$

Then we derive the range of d^*

$$\sqrt{(\frac{p_{i,x}}{\Delta} - (\frac{p_{j,x}}{\Delta} + 1))^2 + (\frac{p_{i,y}}{\Delta} - (\frac{p_{j,y}}{\Delta} + 1))^2} \leq d^* \leq \sqrt{(\frac{p_{i,x}}{\Delta} + 1 - \frac{p_{j,x}}{\Delta})^2 + (\frac{p_{i,y}}{\Delta} + 1 - \frac{p_{j,y}}{\Delta})^2}$$

From the triangle inequality property, such that a, b and c are the length of the triangle edges

$$c \leq a + b$$



We can simplify the range of d^* to

$$\sqrt{\left(\frac{p_{i,x}}{\Delta} - \frac{p_{j,x}}{\Delta}\right)^2 + \left(\frac{p_{i,y}}{\Delta} - \frac{p_{j,y}}{\Delta}\right)^2} - \sqrt{2} \leq d^* \leq \sqrt{\left(\frac{p_{i,x}}{\Delta} - \frac{p_{j,x}}{\Delta}\right)^2 + \left(\frac{p_{i,y}}{\Delta} - \frac{p_{j,y}}{\Delta}\right)^2} + \sqrt{2}$$

$$\frac{d}{\Delta} - \sqrt{2} \leq d^* \leq \frac{d}{\Delta} + \sqrt{2}$$

Hence, the error of d^* is $2\sqrt{2}$ at most.

The rounded integers are indeed the multiple of Δ . Thus the maximum error of a single length is $2\Delta\sqrt{2}$.

Here we have n lengths in the path. Therefore, the total error is:

$$2n\sqrt{2}\Delta = \varepsilon OPT$$

$$\Delta = \frac{\varepsilon OPT}{2n\sqrt{2}}$$

(ii)

Let P and P^* denote set of edges from the optimal solution and the PTAS algorithm respectively and we know that $length^*(P) \geq length^*(P^*)$, then we have

$$\sum_{p_i, p_j \in P^*} d_{ij}^* \leq \sum_{p_i, p_j \in P} d_{ij}^*$$

Thus, we can derive

$$\begin{aligned}
length(P^*) &= \sum_{p_i, p_j \in P^*} d_{ij} \\
&\leq \sum_{p_i, p_j \in P^*} \Delta(d_{ij}^* + \sqrt{2}) \\
&\leq \Delta \sum_{p_i, p_j \in P^*} (d_{ij}^* + \sqrt{2}) \\
&\leq \Delta \left(\sum_{p_i, p_j \in P^*} d_{ij}^* + |P^*| \sqrt{2} \right) \\
&\leq \Delta \left(\sum_{p_i, p_j \in P} d_{ij}^* + |P^*| \sqrt{2} \right) \\
&\leq \Delta \left(\sum_{p_i, p_j \in P} \left(\frac{d_{ij}}{\Delta} + \sqrt{2} \right) + n \sqrt{2} \right) \\
&\leq \Delta \left(\sum_{p_i, p_j \in P} \frac{d_{ij}}{\Delta} + 2n \sqrt{2} \right) \\
&\leq \sum_{p_i, p_j \in P} d_{ij} + \Delta 2n \sqrt{2} \\
&\leq length(P) + \Delta 2n \sqrt{2} \\
&\leq OPT + \left(\frac{\varepsilon OPT}{2n \sqrt{2}} \right) 2n \sqrt{2} \\
&\leq (1 + \epsilon) OPT
\end{aligned}$$

(iii)

Let m^* denote the new boundary of the coordinate after rounding p_x, p_y to p_x^*, p_y^* and we also know that

$$\begin{aligned}
m &= \max(p_x, p_y) \\
OPT &\geq 2m
\end{aligned}$$

Thus

$$\frac{m}{\Delta} \leq m^* \leq \frac{m}{\Delta} + 1$$

Then, we can derive the running time

$$\begin{aligned}
m^* &\leq \frac{m}{\Delta} + 1 \\
&\leq \frac{m2n\sqrt{2}}{\epsilon OPT} + 1 \\
&\leq \frac{m2n\sqrt{2}}{\epsilon 2m} + 1 \\
&\leq \frac{n\sqrt{2}}{\epsilon} + 1
\end{aligned}$$

Therefore, the running time is

$$\begin{aligned}
O(nm^*) &= O\left(n \frac{n\sqrt{2}}{\epsilon} + 1\right) \\
&= O\left(\frac{n^2\sqrt{2}}{\epsilon}\right)
\end{aligned}$$

AIII.3

(i)

Suppose that we have such $ALG(G, \epsilon)$ that can return a $(1-\epsilon)$ -approximation solution to the problem. We can define an FPTAS as follow:

- Set ϵ to some value
- Return $ALG(G, \epsilon)$

The above algorithm runs in polynomial time.

Because we know that $ALG(G, \epsilon) \in \mathbb{N}$, so that if we can find such ϵ that the algorithm yields

$$OPT - 1 < ALG(G, \epsilon) \leq OPT$$

Then, we can get OPT in polynomial time.

In order to get such ϵ , we need:

$$\begin{aligned} ALG(G, \epsilon) &> OPT - 1 \\ &> \left(1 - \frac{1}{OPT}\right) OPT \end{aligned}$$

This holds when $\epsilon < \frac{1}{OPT}$.

Indeed, we do not know the exact value of OPT . But the above property implies that there exists some values of ϵ that can help $ALG(G, \epsilon)$ return OPT . Because our algorithm uses $ALG(G, \epsilon)$ as the main routine, so it also runs in polynomial time.

Now we have an algorithm that can return the optimal solution in polynomial time. Then our problem is not NP-Hard anymore. This contradicts with the definition.

Therefore, there is no FPTAS for the problem.

(ii)

The proof above indeed implies that there exists some values of ϵ that can help any $(1 - \epsilon) - approx$ algorithm return OPT .

Therefore, if there exists a PTAS for this problem, it also returns OPT with such ϵ because PTAS also produces $(1 - \epsilon) - approx$ solutions. This conflicts with the NP-Hard property of the problem as being explained above.

Therefore there is no PTAS for the problem.