Analysis of Low Earth Orbit Satellite Networks with Inter-satellite Links

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Abstract

Low Earth Orbit (LEO) satellite networks are increasingly being deployed to deliver communication services for diverse applications (i.e., voice, data and video). The intersatellite network architecture and routing need to be designed to support these diverse quality of service requirements of each application.

In this work, we evalute a network architecture through a recently proposed metric, namely the *Flow Number*. This metric provides a useful tool to the network architect to choose among several competing designs for the crosslink architecture and gives the designer an measure of the minimum crosslink capacity to support communication between all source-destination pairs. A crosslink architecture with a low flow number is more attractive for satellite networks than the one with a high flow number. We show that the flow number of a a hexagonal satellite constellation network with N nodes is $(N/2)^{1.5}/2$.

Once an architecture is chosen, a routing scheme needs to be developed that can support the service needs of each application. To enhance the reliability and congestion control aspects of the network, multiple paths between a source-destination pair must be known. For this purpose, such paths should be either edge or node disjoint. The earlier studies in this area focussed on finding a set of k disjoint (either edge or node) paths between a pair of source-destination nodes such that the sum of these k path lengths is minimized. However, if the path lengths represent the delay on that path, minimizing the sum of the path lengths may not be very meaningful. In this case, we would like to find a set of k disjoint paths between the source-destination pair such that the length of the *longest* path is the *shortest* among all such sets. In this paper we show that finding a set of k edge-disjoint paths between a source-destination pair such that the length of the *longest* path is the *shortest* among all such sets is NP-complete. We give a mathematical programming formulation for the exact solution of the problem. In addition, we give an approximate solution for the problem with a *guaranteed* performance bound.

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1 Introduction

Low Earth Orbit (LEO) satellite networks are increasingly being deployed to carry out communication of diverse types of traffic [15]. Such networks comprise of ground stations, satellites, ground to satellite links and intersatellite links. Such networks offer a new set of interesting and challenging problems [18]. ATM concepts for such satellite based networks have been proposed in [19].

In [19], the authors introduce the concept of *dynamic virtual topology routing* for routing through networks with time-varying topolgies. In that work, the dynamic network topology is considered to be a periodically repeating series of snapshots of the network topology. Suppose M such snapshots of the topology is considered at intervals of $\Delta t = T/M$, where T is the overall time period. Each of the snapshots at $t = m\Delta t, 0 \leq m \leq M-1$, is modeled as a graph $G(m) = (V, E(m))$, where V is the set of nodes representing the satellites and $E(m)$ represents the set of undirected links between neig'hboring nodes (satellites) existing at time $t = m\Delta t$. Throughout the time period T, a set of unordered $|V|(|V|-1)/2$ source-destination pairs are maintained. The authors suggest assigning a set of $P_w(m)$ of upto k distinct loopless paths to each source-destination pair. Every path $p(m) \in P_w(m)$ comprises of a unique sequence of links $(i,j)_m$. The assignment procedure (whether the link $(i,j)_m$ is part of the path $p(m)$) reflects the set up of an *instantaneous virtual topology* $VT(m)$ within $G(m)$. This task is performed by an iterative k best path search algorithm for every source-destination pair. The authors suggest an iterative approach based on successive calls to the Shortest Path Algorithm due to Dijkstra. They also suggest that by "eliminating" already occupied links, one can force a set of disjoint paths, thus providing a base for simple and robust fault recovery and a framework for traffic flow shaping at the time of operation.

When only considering the intersatellite part of the network, the network topology remains unchanged over time. In this work, two important problems are addresses for routing through the intersatellite part of the network. In the first problem studied in this work, we use a recently proposed graph based metric, the *Flow Number*, to evaluate crosslink architecture of a satellite network. The flow number may be viewed as a measure of the minimum link capacity so that communication between all source-destination pairs can be achieved. This metric is very useful when designing satellite networks and supplements the currently used metrics such as the *diameter* and the *connectivity* for network topology evaluation. A topology with a low flow number is more attractive for satellite networks than one with a high flow number. We show that the flow number of a hexagonal satellite constellation formed with N nodes is $(N/2)^{1.5}/2$.

In the second problem we study disjoint paths in networks. As indicated in the discussion in the earlier, the knowledge of a set of k disjoint (either node or edge) paths between a pair of source-destination nodes can be utilized to enhance the reliability and congestion control aspects of a network. Most of the earlier studies on this topic [1, 5, 9, 11, 14, 16, 17] finds k node or edge disjoint paths between a source-destination node pair such that the sum of the path lengths is minimized. However, if the path lengths represent the delay on that path, minimizing the sum of the path lengths may not be very meaningful. In this case, we would like to find a set of k (node or edge)-disjoint

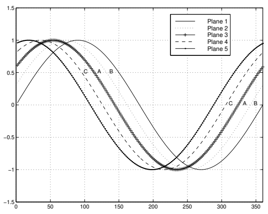

Figure 1: Six planes of LEO constellation illustrating planar relationship

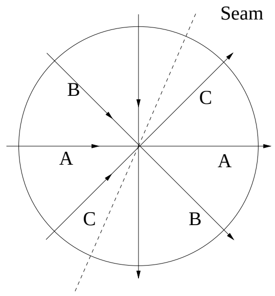

Figure 2: Polar view showing seam

paths between the source-destination node pair such that the length of the *longest* path is *shortest* among all such sets. In this paper we show that finding a set k edge-disjoint paths between the source-destination node pair in an arbitrary graph, such that the length of the *longest* path is *shortest* among all such sets is NP-complete. We give a mathematical programming formulation for the exact solution of the problem. In addition, we give an approximate solution for the problem with a *guaranteed* performance bound.

2 Preliminaries

In a LEO satellite network, each satellite's relationship to their neighbor satellites change as they move through the orbit. The left and right relative satellite neighbors are switched each 180 degrees of the orbit as shown in figure 1. In a satellite constellation there must exist two adjacent planar orbits with satellites moving in opposite orbital directions as shown in figure 2 and this region of the constellation is referred to as the *seam*. Since satellites on either side of the seam are moving in opposite orbital directions, intersatellite communication across the seam is virtually impossible.

If the satellites in the constellation cannot communicate across the seam, then even though the satellite neighbors geographic reference changes (i.e., from right to left) their topological neighbors remain unchanged. Referring to figures 1 and 2, as node A approaches the pole, its right neighbor is node C and its left neighbor is node B. After node A crosses the pole, node B is now its right neighbor and node C is its left neighbor. However, nodes B and C are still neighbors of A. As a result, when only the intersatellite links are considered, the satellite network topology remains unchanged over time. Therefore, routing through the intersatellite part of the network is not a time-vary problem.

A graph where each satellite represents a node and two nodes are adjacent to each other if the satellites represented by these two nodes are connected by an intersatellite link will be referred to as a *satellite graph*. In this paper we consider a satellite constellation where each satellite is connected to six other satellites through intersatellite links. Two of these satellites are in the same satellite plane, two are on the left adjacent plane and

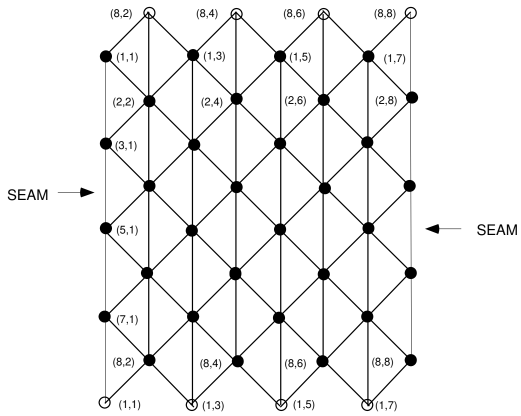

Figure 3: Hexagonal Satellite Grid

two are on the right adjacent plane. An example of such a graph is shown in figure 3.

In the figure, each satellite plane has four satellites indicated by the black nodes and there are eight such planes. In may be noted that the topmost and the bottommost node in one plane is one and the same node. They are drawn this way to indicate that they form an orbit. It may also be noted that every satellite in the constellation has six intersatellite links except the ones on the leftmost and rightmost satellite planes. Since there is no communication across the seam, the satellites on these planes have only four intersatellite links.

3 Flow Number

The metrics like the *connectivity* and the *diameter* of a graph $G = (V, E)$ are used to evaluate the relative merits of different topologies. However, these metrics are unable to capture one important aspect of a network topology. The flow number may be viewed as a measure of the minimum link capacity so that communication between all source destination-pairs can be achieved for a given graph G. This metric is very useful when designing satellite networks and supplements the currently used metrics such as the *diameter* and the *connectivity*, which may be viewed as an indication of the delay through a network topology.

Suppose $d_{i,j}$ is the demand for data stream from node i to node j, $(1 \leq i, j \leq n)$. For example, $d_{i,j}$ may be 1Mbps, implying that 1M bits has to flow from node i to node j per second. Suppose that a demand vector $D = [d_{1,1}, \ldots, d_{n,n}]$ is specified $(d_{i,i} = 0\ \forall i, 1 \leq i \leq n)$. The traffic flow from node i to node j may be routed in many different ways. However, no matter how it is routed, such a flow may be impossible if the capacity (bandwidth) associated with the links is below a certain threshold value. Assuming that the capacity of all the links are identical, we would like to find this minimum threshold capacity of the links such that the demand D can be met through some routing. We refer to this minimum threshold capacity on the links that is able to sustain a traffic flow $d_{i,j} = 1\ \forall i, j,\ i \neq j$, as the *flow number* of the graph $G = (V, E)$.

Formally, the flow number $fn(G)$ of a graph $G = (V, E), (|V| = n, |E| = m)$ may be defined as follows: Suppose that $R_1, \ldots, R_k$ is the set of all possible ways of routing the traffic from the set of sources to the set of destinations. The traffic flow is $d_{i,j} = 1\ \forall i, j,\ i \neq j$. We refer to the traffic from a source i to a destination j as a data stream or a *flow*. Consider a $m \times k$ traffic matix T whose (i, j)-th entry, $T[i, j]$, indicates the number of data streams (or flows) through the edge (link) e_i of the graph $G = (V, E)$ under the routing scheme R_j. Then the flow number of $G = (V, E)$ is

$$fn(G) = \min_{1 \le j \le k} [\max_{1 \le i \le m} T[i, j]]$$

It may be noted that the flow number of a graph can be computed using the techniques known for the *multicommodity flow* problem [7]. In a sense, it can be viewed as the dual of the multicommodity flow problem. In the multicommodity flow problem, the capacity of the links is known and the objective is to find the maximum flow that can be attained, subject to the link capacity constraints. In flow number computation, traffic demand for all source-destination pair is known and the objective is to find the minimum link capacity that will be able to satisfy all the demands.

It may be noted that the notion of *forwarding index* of communication networks introduced by Chung *et. al.* in [4], is somewhat similar to the notion of *flow number* introduced by Sen *et.al.* in [12]. The notion of *node flow number* of a graph $G = (V, E)$, introduced here is the same as the notion of *minimum achievable forwarding index for networks restricted to G* of [4].

It is well known that the multicommodity flow problems are NP-complete [6]. Approximation algorithms for these problems with a guaranteed performance bound is presented in [8, 13]. In the following two subsections, we show that if the graph has a regular structure, the computation of the flow number of a graph is not necessarily all that difficult. We compute the flow number of a satellite constellation where each satellite (except the ones on the orbit boundary) has six intersatelite links. We show that the flow number of a such a constellation with N nodes is $(N/2)^{1.5}/2$.

We compute the flow numbers in the following way: First we compute a lower bound of the flow number and then we compute an upper bound on the flow number and finally we show that these two are equal. Each undirected edge of is replaced by two oppositely directed edges. We compute the minimum capacity on these directed edges that will be able to satisfy the traffic demand of one unit for every source-destination pair ($d_{i,j} = 1 \ \forall i, j, \ i \neq j, d_{i,i} = 0 \ \forall i$).

3.1 Flow Number of Hexagonal Satellite Constellation

Consider the $M \times M$ hexagonal satellite constellation network shown in figure 3 ($M = 8$). It may be noted that the number of satellites in the constellation is $N = 1/2M^2$. Each undirected link of the figure can be thought of as comprising of two oppositely directed links. We show them as undirected links just to keep the diagram uncluttered. For the purpose of analysis we will consider an undirected link as comprising of two oppositely directed links. For simplicity of analysis, we assume that $M = 4m$ for some positive integer m.

Lemma 1 *The lower bound on flow number of a hexagonal satellite constellation network with N nodes is* $(N/2)^{1.5}/2$.

Proof: Omitted due to page restriction.

Lemma 2 *The upper bound on flow number of a hexagonal satellite constellation network with N nodes is* $(N/2)^{1.5}/2$.

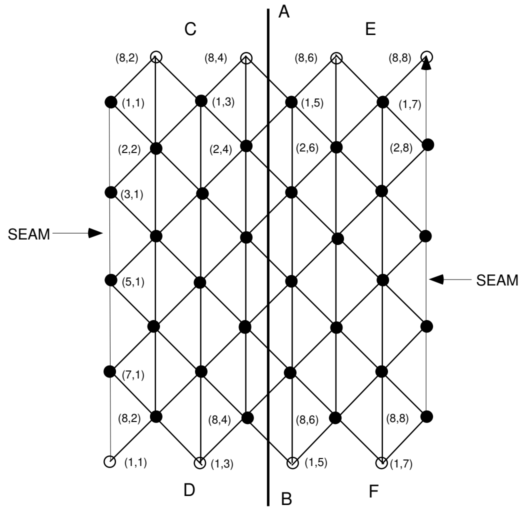

Figure 4: Hexagonal Satellite Grid with the cutline

Proof: The upper bound is established by first describing a routing algorithm. We show that if this algorithm is executed, no directed edge (link) will be required to carry more than a certain number of data streams or flows. This establishes an upper bound on the flow number.

Assume that the satellite grid is divided into two halves by the line AB as shown in figure 4. There are $M^2/4$ nodes on each of these two halves. The $M^2/4$ nodes are distributed in M rows, with each row having $M/4$ nodes. These $M/4$ nodes (the nodes (1,1) and (1,3) in figure 4) have to transfer one data stream to the nodes on the right side (the nodes (1,5) and (1,7) in figure 4). The links $(2,4) \rightarrow (1,5)$ can be used for this purpose. Therefore, the traffic on this links will be $M/4 * M/4 = M^2/16$.

The routing algorithm will route the traffic from a node (i,j) on the left half of the network to a node (k,l) on the right half of the network in the following way ($i < k$ and $j < l$). From (i,j) it will follow the path $(i,j) \rightarrow (i+2,j) \rightarrow (i+4,j) \rightarrow \ldots \rightarrow (k,j)$ or $(i,j) \rightarrow (i+2,j) \rightarrow (i+4,j) \rightarrow \ldots \rightarrow (k+1,j)$ depending on whether or not the node (k,j) exists (e.g., the node (3,2) does not exist). ¿From the node (k,j) (or $(k+1,j)$), it follows the path $(k,j) \rightarrow (k+1,j+1) \rightarrow (k,j+2) \rightarrow \ldots \rightarrow (k,l)$ or $(k+1,j) \rightarrow (k,j+1) \rightarrow (k+1,j+2) \rightarrow \ldots \rightarrow (k,l)$.

In such a traffic routing, each link across the cut line AB will carry exactly $M^2/4 * M/4 = M^3/16$ flows. No link in the network will carry more flows than these links. Thus $M^3/16 = (N/2)^{1.5}/2$ is an upper bound on the flow number of the hexagonal satellite constellation network.

Theorem 3 *The flow number of a hexagonal satellite constellation network with N nodes is* $(N/2)^{1.5}/2$.

Proof: Follows from lemmas 1 and 2.

4 Routing in LEO Satellite Networks

To enhance the reliability and congestion control aspects of the network, multiple paths between a source-destination pair must be known. For reliability and congestion control consideration, such paths should be eitheredge or node disjoint. Disjoint path problems, because of their applications in the design of reliable networks, have been extensively studied [1, 5, 9, 11, 14, 16, 17]. An algorithm for computing a set of k *edge-disjoint* paths between a pair of source and destination nodes, with minimum total edge cost is given in [9]. Suurballe in [16] present an algorithm for the same problem for *node-disjoint* paths. An efficient implementation of the edge-disjoint path problem with minimum total edge cost is given in [17]. Skiscim *et. al.* in [14] study the problem of k successively shortest paths problem. However, in this case the paths are not required to be either node or edge disjoint. Nikolopoulos in [11] studies the k node disjoint paths with minimum total edge cost problem by mapping it into a Trellis graph.

Edge Disjoint k-Path Problem - *Optimization Version*
Instance: A graph $G = (V, E)$, with weight $w_{i,j}$ associated with each edge $e_{i,j}$, $(w_{i,j} \geq 0)$, a source node s, a destination node d and an integer k.
Problem: Find a set of k edge-disjoint paths from s to d such that the length of the *longest* path in this set, is the *shortest* among all such sets of k edge-disjoint paths from s to d.

Edge Disjoint k-Path Problem (EDkPP) - *Decision Version*
Instance: A graph $G = (V, E)$, with weight $w_{i,j}$ associated with each edge $e_{i,j}$, $(w_{i,j} \geq 0)$, a source node s, a destination node d and positive integer k and a non-negative number X.
Question: Is there a set of k edge-disjoint paths from s to d such that the length of the *longest* path in this set is less than or equal to X ?

Theorem 4 *The edge disjoint k-path problem is* NP-complete.

Proof: We show EDkPP is NP-complete by considering a restricted version of the problem where $k = 2$. We call the restricted version as the *Edge Disjoint 2-Path Problem (ED2PP)*.

We show ED2PP is NP-complete by giving a transformation from a well known NP-complete problem - the *partition* problem [6].
Proof: It is easy to see that ED2PP $\in$ NP, since a non-deterministic algorithm need only guess two edge disjoint paths P_1 and P_2 and check in polynomial time that the length of the longer path is less than or equal to X.

We will transform PP to ED2PP. Let the set $A = \{a_1, \ldots a_n\}$ and a "size" $s(a_i) \in Z^+$ for each $a_i \in A, 1 \leq i \leq n$, make up an arbitrary instance of the PP. From this instance of the PP, we must construct a graph $G = (V, E)$ with non-negative weights $w_{(i,j)}$, associated with each edge (i, j), source and destination nodes s and d respectively and a non-negative number X, such that the graph $G = (V, E)$ will have two edge disjoint paths from s to d of length at most X, if and only if the elements of the set A can be partitioned in to two groups, so that the sum of the weights in one group is equal to the sum of the weights in the other group.

We construct the graph $G = (V, E)$ in such a way that it has $3n + 1$ nodes, $(V = \{\{v_i, 0 \leq i \leq n\} \cup \{(u_{i,1}, u_{i,2}),\ 1 \leq i \leq n\}\})$. The directed edges are from
(i) $v_i \rightarrow u_{i+1,1},\ 0 \leq i \leq n-1$, (ii) $v_i \rightarrow u_{i+1,2},\ 0 \leq i \leq n-1$,
(iii) $u_{i,1} \rightarrow v_i,\ 1 \leq i \leq n$, (iv) $u_{i,2} \rightarrow v_i,\ 1 \leq i \leq n$.
Such a graph is shown in figure 5. The weights on the edges are as follows:
(i) $w(v_i, u_{i+1,1}) = 0,\ 0 \leq i \leq n-1$, (ii) $w(v_i, u_{i+1,2}) = 0,\ 0 \leq i \leq n-1$,
(iii) $w(u_{i,1}, v_i) = s(a_i),\ 1 \leq i \leq n$, (iv) $w(u_{i,2}, v_i) = 0,\ 1 \leq i \leq n$
The source node is v_0, the destination node is v_n and $X = 1/2 \sum_{a_i \in A} s(a_i)$.

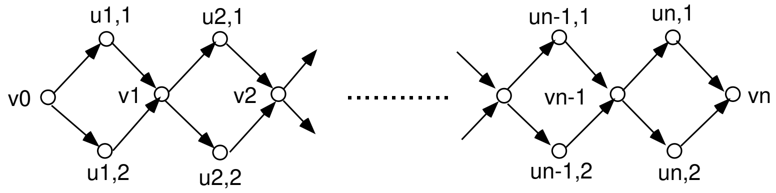

Figure 5: Graph constructed from the instance of the Partition problem

It is easy to see that the construction of the instance of the ED2PP problem can be accomplished in polynomial time. We need to show that instance of the ED2PP problem will have two edge disjoint paths from s to d of length at most X, if and only if elements of the instance of the PP can be divided into two groups, such that the sum of the sizes of the elements in one group is equal to the sum of the size of the elements of the other group.

Suppose that the elements of the set A can be divided into A' and $A - A'$ such that $\sum_{a_i \in A'} s(a_i) = \sum_{a_i \in A-A'} s(a_i)$. In this case we can construct two edge disjoint paths from $s = v_0$ to $d = v_n$ such that the length of the longest path is at most $1/2 \sum_{a_i \in A} s(a_i)$. The paths P_1 and P_2 will have the following directed edges:
(i) $\forall i$, if $a_i \in A'$ the path P_1 will have the edges $v_{i-1} \rightarrow u_{i,1}$ and $u_{i,1} \rightarrow v_i$.
(ii) $\forall i$, if $a_i \in A - A'$ the path P_1 will have the edges $v_{i-1} \rightarrow u_{i,2}$ and $u_{i,2} \rightarrow v_i$.
(iii) $\forall i$, if $a_i \in A'$ the path P_2 will have the edges $v_{i-1} \rightarrow u_{i,2}$ and $u_{i,2} \rightarrow v_i$.
(iv) $\forall i$, if $a_i \in A - A'$ the path P_2 will have the edges $v_{i-1} \rightarrow u_{i,1}$ and $u_{i,1} \rightarrow v_i$.

It can be easily verified that the length of the paths P_1 and P_2 will both be $X = 1/2 \sum_{a_i \in A} s(a_i)$.

Now suppose that the instance ED2PP has two different edge disjoint paths P_1 and P_2 from s to d such that the length of the longer path P_2 is at most $X = 1/2 \sum_{a_i \in A} s(a_i)$. Suppose that the set $N = \{1, 2, \ldots, n\}$. Suppose $M \subseteq N$ is such that the path P_2, is made up of the path segments $v_{m-1} \rightarrow u_{m-1,1} \rightarrow v_m$ for all $m \in M$ and $v_{m-1} \rightarrow u_{m-1,2} \rightarrow v_m$ for all $m \in N - M$. Since the path P_1 is edge disjoint from the path P_2, P_1 is made up of the path segments $v_{m-1} \rightarrow u_{m-1,2} \rightarrow v_m$ for all $m \in M$ and $v_{m-1} \rightarrow u_{m-1,1} \rightarrow v_m$ for all $m \in N - M$. Thus the lengths of the paths P_1 and P_2 are $\sum_{i \in N-M} s(a_i)$ and $\sum_{i \in M} s(a_i)$ respectively. Since the sum of these two path lengths is $\sum_{i \in N} s(a_i) = \sum_{a_i \in A} s(a_i)$ and the length of P_2 is at most $X = 1/2 \sum_{a_i \in A} s(a_i)$, we can conclude that the lengths of the paths P_1 and P_2 are equal to $X = 1/2 \sum_{a_i \in A} s(a_i)$. This implies that $\sum_{i \in M} s(a_i) = \sum_{i \in N-M} s(a_i) = 1/2 \sum_{a_i \in A} s(a_i)$. Thus the elements of the set A can be partitioned into two groups such that the sum of the sizes of the elements of one group is equal to the sum of the sizes of the elements in the other group. This proves the theorem.

Approximate solution to the EDkPP

Consider another edge disjoint path problem with a different objective. This version of the edge disjoint path problem have been studied extensively [9, 16, 17].

Edge Disjoint k-Path Problem - Minimum Total Edge Cost (EDkPP-MTEC)

Instance: A graph $G = (V, E)$, with weight $w_{i,j}$ associated with each edge $e_{i,j}$, $(w_{i,j} \geq 0)$, a source node s, a destination node d and an integer k.

Problem: Find a set of k edge-disjoint paths from s to d such that the sum of the length of the paths in this set, is the *minimum* among all such sets of k edge-disjoint paths from s to d.

Clearly, EDkPP is different from EDkPP-MTEC in its objective. The difficulty of these problems are also different. In this paper, we have shown that the EDkPP is NP-Complete, whereas it is well known that the EDkPP-MTEC can be solved in polynomial time. If n is the number of nodes in the graph and m is the number of edges, then the set of k edge-disjoint paths from a given source s to a given destination d, with minimum total edge cost can be found in $O(km\log_{1+m/n} n)$ time [9, 17].

We use the algorithm to compute the optimal solution to the EDkPP-MTEC problem [9] as an approximate solution to the EDkPP problem. Suppose that the k disjoint paths generated by this algorithm, are $P_1, P_2, \ldots P_k$ and the k disjoint paths that are optimal solution of the EDkPP are $P_1', P_2', \ldots P_k'$. We denote the length of the paths P_i and P_i' by PL_i and PL_i' respectively. Without loss of generality, we assume that $PL_i \leq PL_{i+1}$ and $PL_i' \leq PL_{i+1}'$, for $1 \leq i \leq k-1$.

We measure the quality of the approximate solution to the EDkPP by the ratio PL_k/PL_k'.

Since the path set $P_1, P_2, \ldots P_k$ is the optimal solution to the EDkPP-MTEC problem and the path set $P_1', P_2', \ldots P_k'$ is the optimal solution to the EDkPP problem,

$$PL_1 + PL_2 + \ldots + PL_k \leq PL_1' + PL_2' + \ldots + PL_k'$$

Since $PL_i' \leq PL_{i+1}'$ for $1 \leq i \leq k-1$, the above equation can be rewritten as

$$PL_1 + PL_2 + \ldots + PL_k \leq kPL_k'$$

or $PL_k \leq kPL_k'$ as $PL_i \geq 0$ for $1 \leq i \leq k$. This reduces to

$$PL_k/PL_k' \leq k$$

Thus the ratio of the *approximate solution* to the EDkPP, PL_k, to the *optimal solution*, PL_k', is bounded by k.

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