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Flow Isolation in Power-Efficient Traffic-Grooming Problems in Optical Networks

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ABSTRACT

We address the issue of ensuring the integrity and privacy of communications in optical networks in this paper. For this purpose, the traffic-grooming concept has been extended to include the flow isolation constraints through a multi-class traffic model. We develop ILP formulations and implement and solve them with SAS/OR® OPTMODEL. Our approach guarantees that only traffic components within the same class can be carried on the same wavelength with a relatively small increase in the overall cost.

INTRODUCTION

The demand of telecommunications has grown exponentially in every aspect of the society, business, education, entertainment, government, etc. Networks that can transfer huge amount of telecommunication traffic are needed. Under this situation, optical network appears as an excellent tool, whose capacity is large enough for the current demand. As many critical and sensitive transactions are conducted over the Internet, it is very important to guarantee the integrity and privacy of the information on behalf of the customers. For example, when some business confidential experiments are run by remotely connecting to the server, the Internet provider needs to ensure that the data and the computation results will not be intercepted or tampered with on the way from the use to the server and the way back. Similar situations rise from many other industries, like health care, financial institutions, army and government, and so on.

In this work, our objective is to isolate traffic flows from each other so that the unauthorized eavesdropping or tampering of data is prevented. Electronically routed networks suffer from several challenges since electrical signals could be intercepted, routers could be compromised, and even encrypted transmissions are subject to traffic analysis. On the other hand, optical networks [2], [3] provide several advantages. Particularly, optical signals are difficult to tap, since tampering with an optical fiber causes severe power loss that could be detected immediately; the switching at optical nodes is transparent, which prevents a malicious user from accessing the data passing through; flows traveling on different wavelength cannot interfere with each other in wavelength division multiplexing (WDM) networks.

The traffic grooming problem has been studied extensively. Basic Integer Linear Programming (ILP) formulations can be found in [4] and [8]. In the past studies in traffic grooming problems on networks, most of the attention was focused on how to minimize the total cost of electronic equipment, for example, minimizing the number of SONET add/drop multiplexers (ADMs) in [1], and minimizing the number of lightpaths or transceivers in [7]. Different approaches have been implemented based on the MIP formulations, in general, they could be divided into two classes, first class is to obtain exact solutions of the MIP formulation, and second class is to develop some efficient algorithms by using integer programming tools.

This rest of this report is organized as follows: in Problem Description Section, we explain the problem thoroughly. In Model Formulation Section, we define the ILP model formulation. In Algorithms and Computational Results Section, we develop algorithm for the model proposed, and compare computational results on the sample networks. And we conclude this paper and discuss the future work in Conclusion Section.

PROBLEM DESCRIPTION

The physical topology of optical WDM networks consists of several nodes that are connected with optical fibers, here the fibers are called links. Each link can have at most W wavelengths, and the traffic signals in the network propagate through the optical fiber at different wavelengths. One wavelength has a capacity C, where C is measured in units of traffic. The detailed structure of each node is shown in Figure. 1. Basically, each node is equipped with two parts, optical cross connect (OXC), and digital cross connect (DXC).

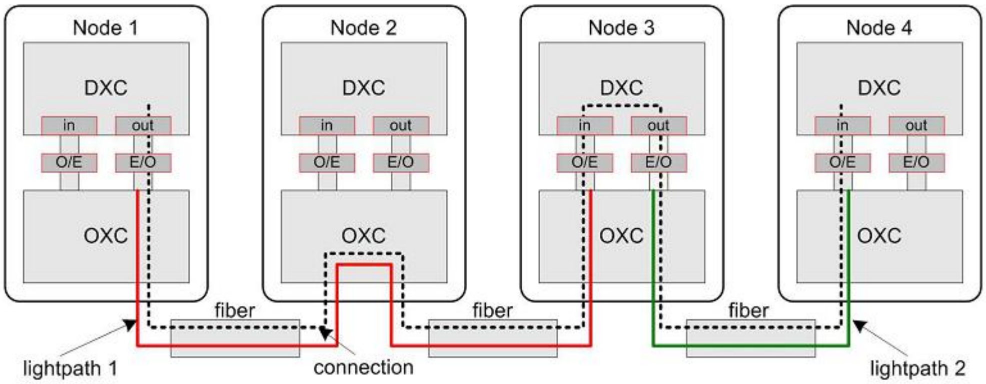


Figure 1: Illustration of an optical WDM network and grooming

Since the traffic signals are transferred at different wavelength on the optical fibers, thus, the network can be alternatively considered as a set of nodes interconnected by lightpath. Here, a lightpath is a path of physical links in which a particular wavelength on each link is reserved for this lightpath. On each lightpath, no optical to electronic traffic signals conversion happens. When the lightpath is terminated at its destination node, the optical signal is converted into electronic signals by transceivers for further processing.

The reason to consider power efficient problem is that, the growth of internet is accompanied by both the increases in the number and power consumption of the network equipments. Besides, the power per byte transmitted has been proven to be a driving force behind the expansion of the network [9], however, the increasing power density threatens the downward trend of it. Therefore, the new question we are facing is how to improve the efficiency of the network, in other words, is how to reduce the power consumption over the whole network.

In this paper, it is assumed that, most of the network power is consumed at the DXC ports connected to the OXC, and in the transceivers which perform the O/E and E/O conversion. If the traffic goes through the OXCs directly, it will not be converted into electronic signals, in this sense, power consumption is reduced.

We express the total power consumption of the whole network in terms of the power consumptions of individual lightpaths. More specifically, the total power consumption is represented as a function of the number of lightpaths and total amount of electronically switched traffic. The first part is considered as fixed cost for setting up a lightpath, and the second part is a linear part associating with the amount of switched traffic.

The so called traffic grooming is used to address the gap between the capacity of wavelength channels and bandwidth requirements of individual traffic demand in wavelength routed WDM networks. The bandwidth of individual traffic demands are usually small compared with the capacity of single wavelength channel, which means, we may aggregate several traffic demands together on the same lightpath.

MODEL FORMULATION

The traffic grooming problem here can be formulated as an ILP problem.

- The physical network is a single-fiber network, i.e., there is at most one fiber between each node pair. Each fiber consists of two links that have opposite directions.
- A lightpath is a directed path from one node to another and occupies the same wavelength channel in every link on it. Once a lightpath is constructed, some security level will be assigned to it. The data with different security level cannot go through this lightpath.
- In each link, a wavelength channel can be assigned to at most one lightpath.
- The demand goes from source node to destination node through the lightpaths. It can be divided into several parts and routed separately. At the starting node of a lightpath, several traffics with the same security level can be combined together, go through the lightpath, and be decomposed at the ending node, as long as they satisfies the capacity constraints. No traffic can be added or dropped in the intermediate nodes of a lightpath.
- The energy consumed at each starting node of a lightpath and consists of a fixed setup cost and a cost proportion to the amount of traffic carried on this lightpath.

The topology of the optical network can be represented as the network $G=(N,l)$, where N is the set of n nodes and L is the set of L directed links. Other notations used in the model are follows.

- L_k^+, L_k^- : the set of links that go out node k and the set of links that come in node k.
- Z : the set of node pairs. $Z = \{(n_1,n_2): n_1, n_2 \in N, n_1 \neq n_2\}$.
- i, j : endpoints of a lightpath.
- s, d : source node and destination node of a demand.
- l : link l in the network.
- R : number of security levels in the problem.
- r : the rth security level.
- W : number of wavelength channels in each link.
- w : the wth wavelength channel in a link.
- C : the capacity of a wavelength channel.
- t_r^{sd} : the demand from node s to node d with security level r.
- P_0 : the energy consumption of constructing a lightpath.
- P_{max} : the energy consumption of a fully used lightpath including constructing consumption.
- p : the energy consumption rate. We have $P_{max} = P_0 + Cp$.
- $b_{ij,r}$: the number of lightpaths starting at node i ending at node j with security level r. This variable is a nonnegative integer.
- $b_{ij,r}^{l}$: number of lightpaths passing through link l, which start at node i and end at node j with security level r. This variable is a nonnegative integer.
- $c_{ij,r}^{w,l}$: binary variable. The value is 1 if some lightpath starting at node i and ending at node j with security level r passes link l and wavelength channel w is assigned to it. Otherwise, the value is 0.
- $t_{ij,r}^{sd}$: the amount of traffic from source s to destination d with security level r that is carried on lightpaths from node i to node j.

Our goal is to minimize the total energy consumed in the network. The objective function is

$$\min \; P_0 \sum_{(i,j)\in\mathcal{Z}} \sum_{r=1}^{R} b_{ij,r} + p \sum_{(s,d)\in\mathcal{Z}} \sum_{(i,j)\in\mathcal{Z}} \sum_{r=1}^{R} c_{ij,r}^{sd} \qquad (1)$$

The traffic grooming problem consists of three groups of constraints.

- Lightpath Routing Constraints

$$\sum\nolimits_{l\in L_k^+} b_{ij,r}^{l} - \sum\nolimits_{l\in L_k^-} b_{ij,r}^{l} = 0 \qquad \forall (i,j)\in\mathcal{Z}, \forall k \in \mathcal{N}\backslash\{i,j\}, \; \forall r = 1,\ldots,R. \qquad (2)$$

$$\sum\nolimits_{l\in L_i^+} b_{ij,r}^{l} = b_{ij,r} \qquad \forall (i,j)\in\mathcal{Z}, \forall r = 1,\ldots,R \qquad (3)$$

$$\sum\nolimits_{l\in L_i^-} b_{ij,r}^{l} = 0 \qquad \forall (i,j)\in\mathcal{Z}, \forall r = 1,\ldots,R \qquad (4)$$

$$\sum\nolimits_{l\in L_j^+} b_{ij,r}^{l} = 0 \qquad \forall (i,j)\in\mathcal{Z}, \forall r = 1,\ldots,R \qquad (5)$$

$$\sum\nolimits_{l\in L_j^-} b_{ij,r}^{l} = b_{ij,r} \qquad \forall (i,j)\in\mathcal{Z}, \forall r = 1,\ldots,R \qquad (6)$$

- Lightpath Wavelength Assignment Constraints

$$\sum_{w=1}^{W} c_{ij,r}^{w,l} = b_{ij,r}^{l} \qquad \forall (i,j) \in \mathcal{Z}, \forall r = 1, \ldots, R, \forall l \in \mathcal{L} \quad (7)$$

$$\sum_{r=1}^{R} \sum_{(i,j)\in\mathcal{Z}} c_{ij,r}^{w,l} \leq 1 \qquad \forall l \in \mathcal{L}, \forall w = 1, \ldots, W \quad (8)$$

$$\sum_{l\in L_k^+} c_{ij,r}^{w,l} - \sum_{l\in L_k^-} c_{ij,r}^{w,l} = 0 \qquad \forall (i,j) \in \mathcal{Z}, \forall k \in \mathcal{N}\backslash\{i,j\}, \forall r = 1, \ldots, R, \forall w = 1, \ldots, W \quad (9)$$

- Traffic Routing Constraints

$$\sum_{(s,d)\in\mathcal{Z}} t_{ij,r}^{sd} \leq b_{ij,r} \cdot C \qquad \forall (i,j) \in \mathcal{Z}, \forall r = 1, \ldots, R \quad (10)$$

$$\sum_{(s,d)\in\mathcal{Z}} t_{ij,r}^{sd} \geq (b_{ij,r} - 1) \cdot C \qquad \forall (i,j) \in \mathcal{Z}, \forall r = 1, \ldots, R \quad (11)$$

$$\sum_{j\in\mathcal{N}\backslash\{i\}} t_{ij,r}^{sd} - \sum_{j\in\mathcal{N}\backslash\{i\}} t_{ji,r}^{sd} = 0 \qquad \forall (s,d) \in \mathcal{Z}, \forall i \in \mathcal{N}\backslash\{s,d\}, \forall r = 1, \ldots, R \quad (12)$$

$$\sum_{j\in\mathcal{N}\backslash\{s\}} t_{sj,r}^{sd} = t_r^{sd} \qquad \forall (s,d) \in \mathcal{Z}, \forall r = 1, \ldots, R \quad (13)$$

$$\sum_{j\in\mathcal{N}\backslash\{s\}} t_{js,r}^{sd} = 0 \qquad \forall (s,d) \in \mathcal{Z}, \forall r = 1, \ldots, R \quad (14)$$

$$\sum_{j\in\mathcal{N}\backslash\{d\}} t_{jd,r}^{sd} = t_r^{sd} \qquad \forall (s,d) \in \mathcal{Z}, \forall r = 1, \ldots, R \quad (15)$$

$$\sum_{j\in\mathcal{N}\backslash\{d\}} t_{dj,r}^{sd} = 0 \qquad \forall (s,d) \in \mathcal{Z}, \forall r = 1, \ldots, R \quad (16)$$

The above formulation is based on the flow conservation principle.

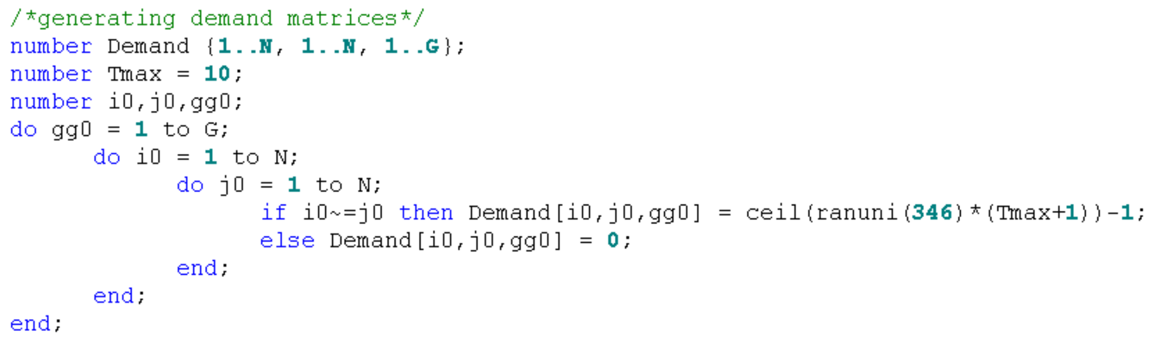
- Equation (1) represents the energy consumption in the network.
- Equations (2) - (6) ensure that, for each pair of nodes, the lightpaths starting from one node and ending with the other node can be properly routed. As we can see, if we treat $b_{ij,r}$ as the demands in a multicommodity flow problem, then this part of constraints form many smaller size multicommodity flow problem.
- Equation (7) makes the wavelength channels in each link to be assigned to the relevant lightpaths.
- Equation (8) shows that each wavelength channel is assigned to at most one lightpath.
- Equation (9) is the wavelength channel conservation principle, which ensures the wavelength channels used at each node can form lightpaths properly.
- Equations (10) and (11) make the lightpaths to be fully used.
- Equations (12) and (16) are the traffic conservation principle. These constraints determine how the traffic are routed after the lightpaths were set up.

It is worth mentioning that our formulation is not a polynomial of the input size of the problem. Since the number of variables and the number of constraints are all linear to *W* instead of *log(W)*, they will grow exponentially as the size of the problem grows. The decision version of this problem is NP-complete even if we restricted the problem to the case: P_0=1, p=0, R=1 and the network is a path network [5]. Therefore, the complexity of the optimization version is NP-hard.

ALGORITHMS AND COMPUTATIONAL RESUTLS

As is discussed above, the problem in this report is NP-hard. To find the exact optimal solution, we use the Branch and Bound algorithm to solve the problem. We implement this algorithm and solve several test models in SAS/OR®. In this section, firstly, we test several examples to see how the computing time increases as the problem size increases. Then, we try to apply some simple rules so that an incumbent can be found easier in the Branch and Bound algorithm.

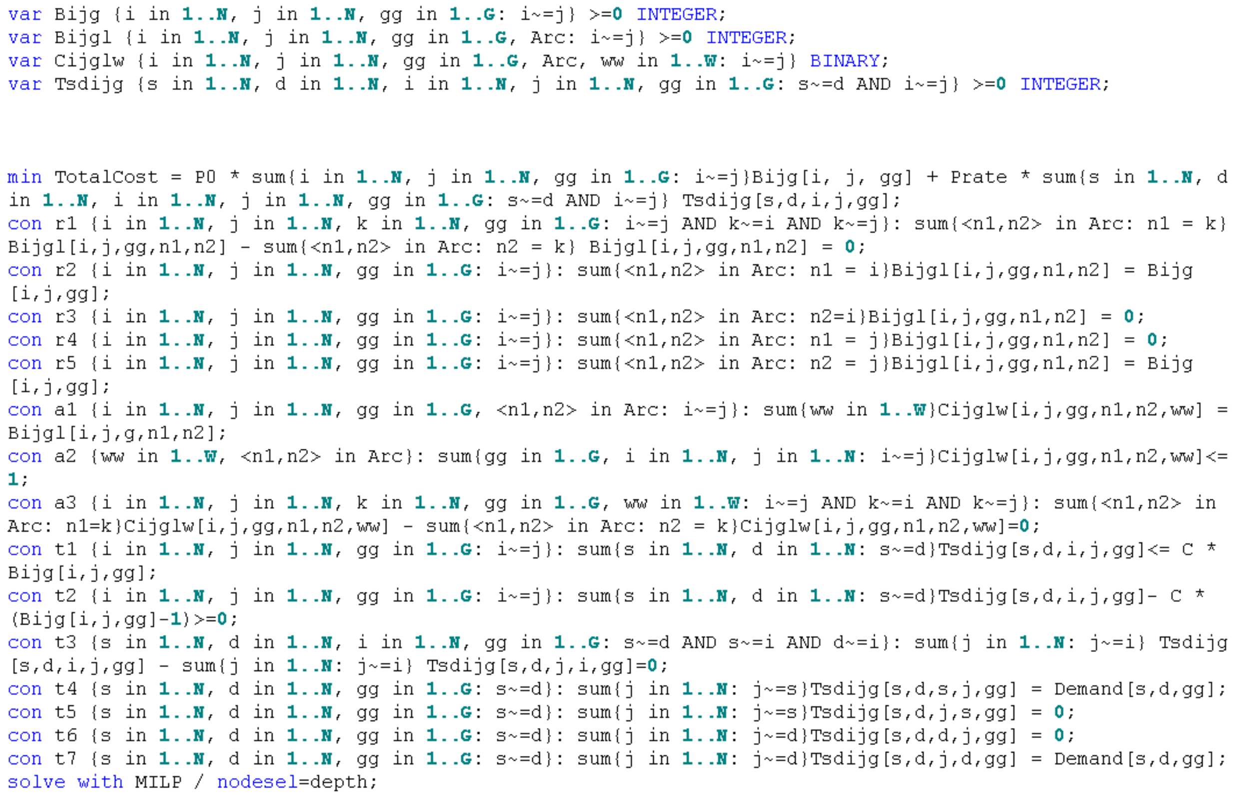
In the numerical experiments, for each pair of node in *Z*, the demand has a uniform distribution [0, T_{max}]. The SAS® code for generating the traffic matrix is as follows (Figure 2):



```
/*generating demand matrices*/
number Demand {1..N, 1..N, 1..G};
number Tmax = 10;
number i0,j0,gg0;
do gg0 = 1 to G;
      do i0 = 1 to N;
            do j0 = 1 to N;
                  if i0~=j0 then Demand[i0,j0,gg0] = ceil(ranuni(346)*(Tmax+1))-1;
                  else Demand[i0,j0,gg0] = 0;
            end;
      end;
end;
```

Figure 2: SAS® Code for Generating Traffic Matrix

The SAS® code for the model formulation is given below (Figure 3).



```
var Bijg {i in 1..N, j in 1..N, gg in 1..G: i~=j} >=0 INTEGER;
var Bijgl {i in 1..N, j in 1..N, gg in 1..G, Arc: i~=j} >=0 INTEGER;
var Cijglw {i in 1..N, j in 1..N, gg in 1..G, Arc, ww in 1..W: i~=j} BINARY;
var Tsdijg {s in 1..N, d in 1..N, i in 1..N, j in 1..N, gg in 1..G: s~=d AND i~=j} >=0 INTEGER;



min TotalCost = P0 * sum{i in 1..N, j in 1..N, gg in 1..G: i~=j}Bijg[i, j, gg] + Prate * sum{s in 1..N, d
in 1..N, i in 1..N, j in 1..N, gg in 1..G: s~=d AND i~=j} Tsdijg[s,d,i,j,gg];
con r1 {i in 1..N, j in 1..N, k in 1..N, gg in 1..G: i~=j AND k~=i AND k~=j}: sum{<n1,n2> in Arc: n1 = k}
Bijgl[i,j,gg,n1,n2] - sum{<n1,n2> in Arc: n2 = k} Bijgl[i,j,gg,n1,n2] = 0;
con r2 {i in 1..N, j in 1..N, gg in 1..G: i~=j}: sum{<n1,n2> in Arc: n1 = i}Bijgl[i,j,gg,n1,n2] = Bijg
[i,j,gg];
con r3 {i in 1..N, j in 1..N, gg in 1..G: i~=j}: sum{<n1,n2> in Arc: n2=i}Bijgl[i,j,gg,n1,n2] = 0;
con r4 {i in 1..N, j in 1..N, gg in 1..G: i~=j}: sum{<n1,n2> in Arc: n1 = j}Bijgl[i,j,gg,n1,n2] = 0;
con r5 {i in 1..N, j in 1..N, gg in 1..G: i~=j}: sum{<n1,n2> in Arc: n2 = j}Bijgl[i,j,gg,n1,n2] = Bijg
[i,j,gg];
con a1 {i in 1..N, j in 1..N, gg in 1..G, <n1,n2> in Arc: i~=j}: sum{ww in 1..W}Cijglw[i,j,gg,n1,n2,ww] =
Bijgl[i,j,g,n1,n2];
con a2 {ww in 1..W, <n1,n2> in Arc}: sum{gg in 1..G, i in 1..N, j in 1..N: i~=j}Cijglw[i,j,gg,n1,n2,ww]<=
1;
con a3 {i in 1..N, j in 1..N, k in 1..N, gg in 1..G, ww in 1..W: i~=j AND k~=i AND k~=j}: sum{<n1,n2> in
Arc: n1=k}Cijglw[i,j,gg,n1,n2,ww] - sum{<n1,n2> in Arc: n2 = k}Cijglw[i,j,gg,n1,n2,ww]=0;
con t1 {i in 1..N, j in 1..N, gg in 1..G: i~=j}: sum{s in 1..N, d in 1..N: s~=d}Tsdijg[s,d,i,j,gg]<= C *
Bijg[i,j,gg];
con t2 {i in 1..N, j in 1..N, gg in 1..G: i~=j}: sum{s in 1..N, d in 1..N: s~=d}Tsdijg[s,d,i,j,gg]- C *
(Bijg[i,j,gg]-1)>=0;
con t3 {s in 1..N, d in 1..N, i in 1..N, gg in 1..G: s~=d AND s~=i AND d~=i}: sum{j in 1..N: j~=i} Tsdijg
[s,d,i,j,gg] - sum{j in 1..N: j~=i} Tsdijg[s,d,j,i,gg]=0;
con t4 {s in 1..N, d in 1..N, gg in 1..G: s~=d}: sum{j in 1..N: j~=s}Tsdijg[s,d,s,j,gg] = Demand[s,d,gg];
con t5 {s in 1..N, d in 1..N, gg in 1..G: s~=d}: sum{j in 1..N: j~=s}Tsdijg[s,d,j,s,gg] = 0;
con t6 {s in 1..N, d in 1..N, gg in 1..G: s~=d}: sum{j in 1..N: j~=d}Tsdijg[s,d,d,j,gg] = 0;
con t7 {s in 1..N, d in 1..N, gg in 1..G: s~=d}: sum{j in 1..N: j~=d}Tsdijg[s,d,j,d,gg] = Demand[s,d,gg];
solve with MILP / nodesel=depth;
```

Figure 3: SAS® Code for Model Formulation

The networks used in the numerical experiments can be seen in Figure 4.

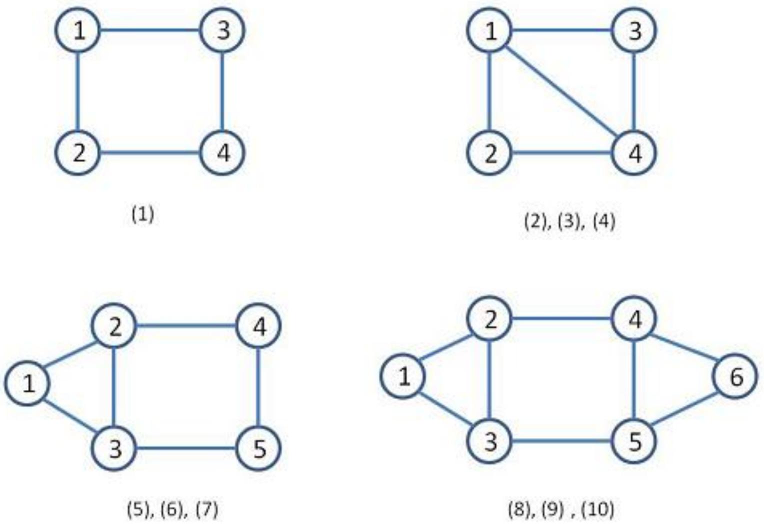


Figure 4: Network used as experiments.

In test example (1), the network is a ring network with 4 nodes. The number of security level is R=2. In this case, T_{max}= 10. In test examples (2), (3) and (4), the network is a mesh network with 4 nodes. The number of security level is R=2 in (2) and (3), and R=3 in (4). In these cases, T_{max}= 10 in (3) and (4), and T_{max}= 3 in (2).

Below is the output for test example (4) (Figure 5).

```
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           The OPTMODEL Procedure

              Problem Summary

  Objective Sense            Minimization
  Objective Function            TotalCost
  Objective Type                   Linear

  Number of Variables                1908
  Bounded Above                         0
  Bounded Below                       828
  Bounded Below and Above            1080
  Free                                  0
  Fixed                                 0
  Binary                             1080
  Integer                             828

  Number of Constraints              1110
  Linear LE (<=)                       66
  Linear EQ (=)                      1008
  Linear GE (>=)                       36
  Linear Range                          0
               The SAS System      15:41 Tuesday, September 21, 2010   63

           The OPTMODEL Procedure

             Solution Summary

   Solver                           MILP
   Objective Function          TotalCost
   Solution Status               Optimal
   Objective Value                7.6094
   Iterations                      37020
   Nodes                             287

   Relative Gap                        0
   Absolute Gap                        0
   Primal Infeasibility     3.4031922E-7
   Bound Infeasibility      5.6842105E-7
   Integer Infeasibility    3.8952379E-6
```

The summary of the results of test (1), (2), (3) and (4) can be seen in Table 1. It should be mentioned that the number of variables and number of constraints are the results after the presolve procedure in SAS/OR®.

Among the four experiments, the first network is the simplest one and hence requires the least running time. Even in these simple cases, there are still more than five hundreds binary or integer variables. When the security level increases from R=2 to R=3, the size of the problem increases nearly a half, which complies with our intuition.

Test No.	Node	Link	R	No. Var	No. Con	BB Node	Gap	Time
(1)	4	4	2	587	470	81	0	19.75
(2)	4	5	2	703	520	69	0	41.36
(3)	4	5	2	723	528	48	0	23.43
(4)	4	5	3	1077	774	286	0	191

Table 1: Summary results of tests (1), (2), (3) and (4).

When the number of nodes in the network goes to 5, the problem becomes even harder. As is shown in Table 2, in test (5), SAS/OR® solver with the default setting finds a feasible solution in near 600 seconds and this solution is at most 1.91% larger than the optimal solution. However, the solver does not return any further information in the next three hours. The case is similar when the number of nodes in the network goes to 6 in test (8). The solver does not provide any information after 5077 seconds. In this test, the solver was terminated after running for more than 17 hours.

Test No.	Node	Link	R	No. Var	No. Con	BB Node	Gap	Time
(5)	5	6	2	1751	1146	>1300	1.91%	>600
(6)	5	6	2	1379	910	4007	4.56%	386
(7)	5	6	2	1751	1146	>7900	1.71%	>1083
(8)	6	8	2	3930	2244	>5200	5.35%	>5077
(9)	6	8	2	3586	2140	871	3.03%	598
(10)	6	8	2	3930	2244	>12300	1.42%	> 10795

Table 2: Summary results of tests (5), (6) and (7).

Based on this situation, we need to use heuristics to solve for a feasible solution in reasonable time. As we can see, in the variables $b_{ij,r}^{l}$, $c_{ij,r}^{w,l}$, and $t_{ij,r}^{sd}$,the link l may be far from lightpath (i,j) and lightpath (i,j) may also be far from the source s and destination d, while the nodes s and d are possibly quite near and nodes i and j are possibly quite near, in the sense that the distances between two nodes are measured by the shortest path via setting the length of each link be 1. In the optimal solution, for two nodes that are near, there may exist a lightpath linking them and passing through several links far from them. But in a feasible solution, such situation may not exist, since a long lightpath can always separated into several shorter lightpaths. Another view is that, in the real world, the demand between every two nodes may exist. If too many long lightpaths are set up, then the resources for carrying those short distance traffic will be reduced significantly. Therefore, one intuition is that, firstly, we divided the network into several subnetworks. Then, set lightpaths on those links connecting sub networks. After that, solve the problem with these lightpaths being fixed.

When a feasible solution is obtained by the heuristic above, we can either use it as our final solution or put it as an incumbent in the Branch and Bound algorithm. In test (6), link (4, 5) is fixed, and in test (9), link (3,5) is fixed. As we can see in tests (6) and (9), a feasible solution is obtained in several minutes. The gap between the feasible solutions and the optimal solutions are not large. In tests (7) and (10), after putting the feasible solution into the Branch and Bound algorithm as an incumbent, the solver can move further and get better solutions. Although the solver still cannot get the optimal solution in a reasonable time, we get some feasible solutions in a much shorter time and their performances are not bad.

CONCLUSION

In this study, we introduced the power efficient traffic grooming problem with isolation constraints. This problem considered both the energy consumption issues and the network security issues. An ILP formulation is given in this report and computational results of several examples are given. We also provide an idea to reduce the running time for finding a good feasible solution as the incumbent of the Branch and Bound algorithm used in the experiments.

For the future work, firstly, we will try to find a polynomial formulation of this problem in the future. Secondly, more instances need to be tested to get a general idea of how to fix critical links. Thirdly, for those networks that do not have clear structure that can be used to determine sub networks, other heuristics needs to be developed.

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