A Low-Cost Design of Next Generation SONET/SDH Networks with Multiple Constraints.

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Abstract— ***This study investigates the problem of ring-node assignment in a Multiservice SDH/SONET Optical network design with Network capacity constraint.***

The problem is characterized as a graph-partitioning problem, and a heuristic algorithm based on constraints programming satisfaction technology is proposed. The algorithm is tested in OPNET simulation environment using different network models derived from a hypothetical case study of an optical network design for Bellville area in Cape Tow, South Africa. Data are collected for analysis from the simulation, and the number and the capacity of nodes and ring are the control variables under investigation.

Simulation results for the different network model under uniform and non-uniform traffic demands are reported. The algorithm is able to return a solution with a performance measure that is close to optimal.

Index Terms—**Multiservice provisioning platform (MSPP), SONET/SDH, Constraints satisfaction programming.**

I. INTRODUCTION

Multiservice provisioning platform (MSPP) is a leading-edge technology that re-engineered the legacy Synchronous Digital Hierarchy (SDH) Optical networks to address the demand for the transmission of numerous new services which are mostly IP-based. In network designs using this technology, ring architecture is more favoured for its offer of very fast restoration capabilities in the event of a single network node failure.

The building block for ring architecture is the MSPP. Multiple MSPP located at sparsely distributed customer sites can be daisy-chained to form access ring for either bi-directional or unidirectional traffic flow. MSPP of greater switching capacity otherwise known as MSSP (Multiservice Switching Platform), interconnect a number of access rings to the backbone ring. Moreover, the design of backbone ring requires that the number of connected access rings must be minimised in order to reduce the overall network cost.

Within each node (MSSP and MSPP) are a group of hardware called Digital Cross Connect (DXC) and Add/Drop Multiplexer (ADM), whose cost determines the node cost. In a similar manner, a network design should also optimize the placement and the number of this hardware in the node (MSPP) to minimize the cost of the design.

The objective function is to minimize both the number of access rings and the number of nodes installed on each ring to reduce the overall cost of the network design.

A solution to such design and planning problems is complex and difficult to solve due to the number of constraints involved. It is often decomposed into a sequence of small, easier to manage sub-problems in order to solve it. Most times, it may be necessary to divide each sub-problem into smaller sub-problems, and every problem units modeled using Integer Linear Programming (ILP). This action will certainly generate a list of inequality equations, each defining one or more constraints. It is necessary to solve each of these equations in order to obtain an optimum design solution.

Over the past few years, many research activities have made considerable efforts to solve this problem ([1] and [2]) by developing many ILP-based heuristic algorithms. The intractable nature of this approach led to introduction of a workaround solution method whereby the variables defining the constraints are loosely assumed to be *0 -1* rather than using arbitrary integer. Paradoxically, the problem of solving *0 -1* ILP is still non-trivial and therefore classified as *NP-hard* in literature [3]. In addition, few of these studies also include optical constraints and node interface capacity constraints issue into their design considerations. This is done because there is an increasing concern on the impacts of differential delay restriction on the new set of network services.

The growing number of constraints gives an indication that ILP may not be very suitable design approach, most especially for the design of the backbone ring of next generation optical networks. We therefore propose a new design technique that will better handle all the sets of constraints to be satisfied in terms of computational time and efficiency, and as well, utilize minimum number of access rings.

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We commence this work by reviewing the Integer linear programming and constraints satisfaction programming approaches of solving ring assignment problem. Section III discusses the design process. Here, related issues such as network traffic capacity planning and logical topology designs are examined. In section IV, we present our proposed algorithm based on constraints satisfaction programming, and finally section V discusses the simulation results.

II. SONET/SDH RING ASSIGNMENT PROBLEM

A. *Integer Linear Programming approach*

SDH ring assignment problem primarily deals with ways of minimising the number of local rings that are interconnected by the backbone ring, generically referred to as federal ring.

It is assumed that the total amount of traffic on all the local rings must be less than or equal to the capacity of the backbone network. Each site on the local rings interconnected by federal rings must be connected by another special device back-to-back, and is known as MultiService Switching Platform (MSSP). The number of local rings determines the number of MSSP required, and if this is added to the number of MSPP, then overall network cost will increase. It is therefore possible to argue for the strong need of node and ring optimisations in order to reduce network cost.

The work of [1] that was further investigated by [2] adopted Integer linear programming and heuristic algorithm approaches in order to minimise the network cost.

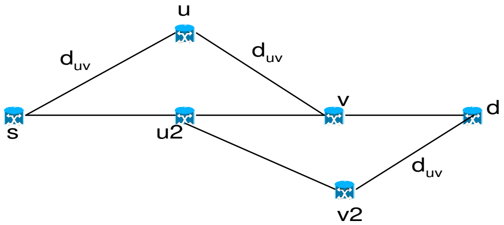


Fig. 1. Treaging Network of nodes and links assignment treated as graph partitioning problem.

The problem is analysed and treated as a graph partitioning problem using an undirected graph G = (V, E), with integers *B* and *K,* and a non negative edge weight d_{uv} associated with each edge (u, v). This problem is considered NP complete. The question raised is that: Is there a partition of V into K disjoint sets V_1, V_2…………V_k such that:

$$\sum_{u\in vi, v\in vi, u\prec v} d_{uv} + \sum_{u\in vi; u\notin vi} d_{uv} \le B \tag{1}$$

$$\sum_{i-1}^{k-1} \sum_{j=i+1}^{k} \sum_{u\in vi} \sum_{v\in vj} d_{uv} \le B \tag{2}$$

for i=1,2,..................k, and

In eq.1, the first term computes the traffic between any two sites in the ring and the second term computes the traffic between the sites outside the ring and the sites in the ring. Similarly, eq.2, computes total traffic on the federal ring and it is less than or equal to the common bandwidth capacity *B*.

In their results, the algorithm proposed finds the optimal solution that minimises the upper bound of number of local rings interconnected by the federal rings for reduced network cost.

Nevertheless, a recently conducted industrial research [4] shows that the minimum number of OC-48 (OC-92 equivalent) rings in the CO (Central Office) is between 8 and 12 to justify the use of MSSP. With this it makes economic sense to deploy single MSSP that can aggregate multiple rings than single ADM for each of the rings. This implies that any serious attempt to reduce the network cost, node cost must also be considered.

B. *Constraint Satisfaction Programming (CSP) approach*

This technique has been used in many academic and research parlance to tackle a wide range of search problems including resource allocation, transportation, planning and scheduling.

It is defined by a finite set of variables, constraints and domain. The domain is a set of values for each variable, and each constraint involves some subsets of variables and specifies the allowable combinations of values of that subset.

Usually, the problem is stated by assignment of values to some or all of the variables. Any complete assignment that satisfies all the constraints is a solution to a pre-defined problem.

Generically, there are two techniques for solving constraint satisfaction problem, viz: consistency and search techniques. Search technique is more favoured due to its completeness in searching for a possible solution, although it can be very slow.

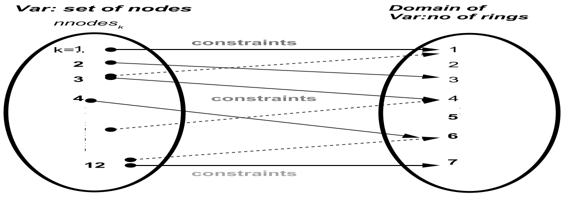


Fig. 2. Modeling SDH Ring assignment problem using Constraints Satisfaction Programming (CSP).

Figure 2 represents the generic concept of constraints satisfaction programming. Both the set of nodes and rings are defined and implicitly declared but not typed (unlike in other languages) as variables (var). Each of the nodes has a domain of the set of rings. For example node 3 = { 1, 4} implies that node 3 can either be assigned to ring 1 or 4, given that a node can not be assigned to two or more rings. Similarly, node 12 = {6, 7} indicates that node12 can be assigned to ring 6 or 7, and not to both rings.

It is syntactically correct to represent the above example thus: $R_1(\chi,\varphi) \leftarrow N_3$

Whereby χ, and φ are the constraints used to define the problem instance.

III. DESIGN CONSIDERATIONS

This section discusses the design procedure. Capacity planning was conducted for different categories of business and residential users in order to determine the capacity of the access and federal rings. According to [7], the outcome of this capacity plan computation will drive technology and equipment specifications in terms of bandwidth requirements. Next, the link and ring design were computed to pave the way for logical topology design.

A. *Network Capacity Planning*

It is assume that there are up to 250 sites in our network coverage area (as shown in figure 3), and each one is considered a Multi Tenant Unit (MTU) housing 50 small businesses, and 5 large businesses. Each of the 50 small businesses has 1 user and each of the large businesses has 100 users. These numbers of users (1:100) for different categories of businesses are refers to as diversity factor.

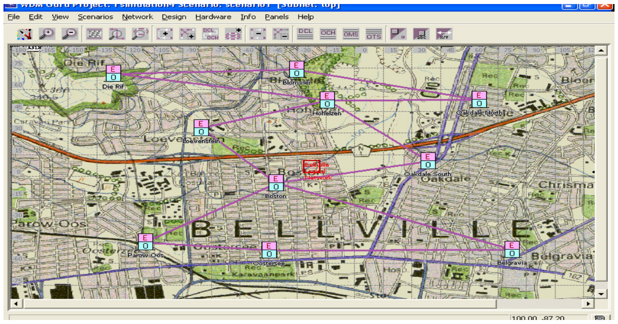


Fig. 3. The fiber routing plan of Network coverage area.

Also, a 64-kbps non-normalised voice grade bandwidth and 144-kbps non-normalised data bandwidth is allocated per user. In Table I, *SB* represents small business, *LB* represents large business, *SBv* represents small business voice bandwidth, *SBd* represents small business data bandwidth, *LBv* represents large business voice bandwidth *LBd* represents large business data bandwidth, and *BR* represents total bandwidth request per site, and nodes 0-12 each of which represents clients' sites located at selected point within the area.

In this case, we lit-up only the first-twelve sites in pilot run, and similar procedure can as well be used to deploy the remaining 138 sites.

TABLE I

ESTIMATION OF TOTAL TRAFFIC NETWORK CAPACITY FOR PILOT DEPLOYMENT

Sites	No of users (unit counts)		contributed bandwidth (Mbps)				Total Per sites
	SB	LB	SBv	SBd	LBv	LBd	BR
N0	50	800	3.2	7.2	57.6	115.2	183.2
N1	50	800	3.2	7.2	57.6	115.2	183.2
N2	50	800	3.2	7.2	57.6	115.2	183.2
N3	50	800	3.2	7.2	57.6	115.2	183.2
N4	50	800	3.2	7.2	57.6	115.2	183.2
N5	50	800	3.2	7.2	57.6	115.2	183.2
N6	50	800	3.2	7.2	57.6	115.2	183.2
N7	50	800	3.2	7.2	57.6	115.2	183.2
N8	50	800	3.2	7.2	57.6	115.2	183.2
N9	50	800	3.2	7.2	57.6	115.2	183.2
N10	50	800	3.2	7.2	57.6	115.2	183.2
N11	50	800	3.2	7.2	57.6	115.2	183.2
Sum of bandwidth from all nodes (N0-N11)							2198
Normalised bandwidth (1:10) oversubscription							219.8

Using the stated diversity factor, the bandwidth requirements for each MTU were computed, and the contributed bandwidths for the 12 sites add to a total of 2,198.6 Mbps. After normalisation to compensate for oversubscription, the total becomes 219.8 Mbps.

B. *Logical Topology Design*

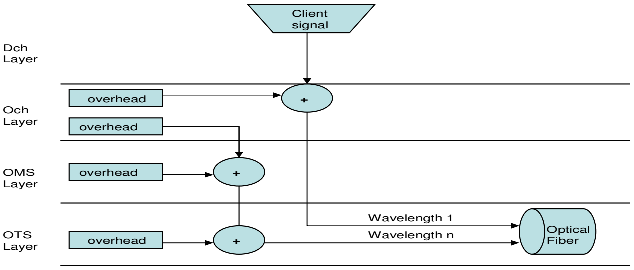


Fig. 4. Optical Transport network layering.

From the design point of view, logical design can be divided into two stages:

- ➢ The traffic demand estimate
- ➢ The link design

B1. Traffic demand estimate

The two types of user's traffic considered for a logical (or virtual) topology design are uniform and non-uniform. A 12 by 12 traffic matrix was generated in the network by setting the traffic demand between each node pair as 4 units. The total network traffic capacity is then added together as 264 as calculated below.

Fig. 5. Traffic flow between node pair.

Let ρ_{ij} represents traffic from node i to node j, and ρ_{ji} represents traffic in the opposite direction.

Let ρ_v represents the offered load, i.e. the traffic demand per node pair. Because, a bidirectional traffic matrix is considered in this design, it is reasonable to assume that:

$$\rho_{ij} = \rho_{ji} \tag{3}$$

Provided the traffic is uniformly distributed and a balance load system is considered. In this case, the traffic flow from each node is equal to half of the total offered load between the node pair.

Also, $$0 \le \rho_v \le 4 \tag{4}$$

But for this particular case ρ_v is chosen as 4 units and N is given as the number of nodes in the network. Then the total traffic capacity is thus given as:

$$N(N-1)\rho_v \tag{5}$$

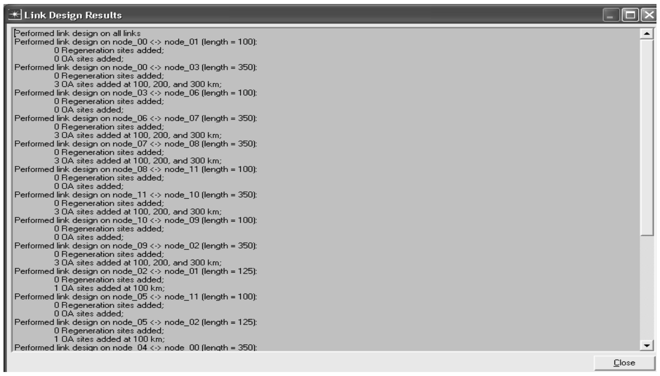
Given that there are 12 nodes in the hypothetical network used as case study, the network traffic capacity is 12 (12-1) 4 = 528 units.

In Bidirectional Line Switched Ring (BLSR) configuration, the working path carries only one half of the total traffic capacity. This implies that the traffic capacity in this network is only 264 units.

It is interesting to know that irrespective of whether the traffic distribution is uniform or non-uniform, the total traffic capacity remained the same.

B2. The Link and Ring design

The result obtained from traffic demand estimation is used to design the ring. However, prior to the ring design, it is important to do optical transport system (OTS) link design. With this, it would be possible to calculate the number of amplifiers and regenerators required on each link. Long fiber link are susceptible to signal degradation and as such signal must be amplified and regenerated at regular intervals. All fibers are equipped LH-40 line system with only one active wavelength per fiber strand, and the span length is set to 100.0 meters with maximum of '6' OA per (optical amplifiers) per link. LH-40 indicates that the line is a Long Haul with a total of 40 channels per fiber strand. The outcome of the design with a list of sites added on each link as shown in Figure 6.



```
Performed link design on all links
Performed link design on node_00 <-> node_01 (length = 100):
          0 Regeneration sites added;
          0 OA sites added;
Performed link design on node_00 <-> node_03 (length = 350):
          0 Regeneration sites added;
          3 OA sites added at 100, 200, and 300 km;
Performed link design on node_03 <-> node_06 (length = 100):
          0 Regeneration sites added;
          0 OA sites added;
Performed link design on node_06 <-> node_07 (length = 350):
          0 Regeneration sites added;
          3 OA sites added at 100, 200, and 300 km;
Performed link design on node_07 <-> node_08 (length = 350):
          0 Regeneration sites added;
          3 OA sites added at 100, 200, and 300 km;
Performed link design on node_08 <-> node_11 (length = 100):
          0 Regeneration sites added;
          0 OA sites added;
Performed link design on node_11 <-> node_10 (length = 350):
          0 Regeneration sites added;
          3 OA sites added at 100, 200, and 300 km;
Performed link design on node_10 <-> node_09 (length = 100):
          0 Regeneration sites added;
          0 OA sites added;
Performed link design on node_09 <-> node_02 (length = 350):
          0 Regeneration sites added;
          3 OA sites added at 100, 200, and 300 km;
Performed link design on node_02 <-> node_01 (length = 125):
          0 Regeneration sites added;
          1 OA sites added at 100 km;
Performed link design on node_05 <-> node_11 (length = 100):
          0 Regeneration sites added;
          0 OA sites added;
Performed link design on node_05 <-> node_02 (length = 125):
          0 Regeneration sites added;
          1 OA sites added at 100 km;
Performed link design on node_04 <-> node_00 (length = 350):
```

Fig. 6. Screenshot of Link design result showing fiber length and equipment.

The above screenshot is the result of the OTS link design. It shows that, for example the link between Blomvlei and Hohelzen has a fiber length of 125 km with no regenerator (R) and 1 optical amplifier (OA) at 100km.

Using the fiber routing plan in Fig. 3, the network lends itself into a 7-ring topology. For the original network configuration, the ring that spans across nodes "Blomvlei-Oakdale South-Boston-Hohelzen" has maximum of four distinct nodes, each node is a matching node that interfaces with four other rings with an even bandwidth distribution. For the sake of clarity, the ring with four distinct nodes was used to represent the core ring. Such nodes are often reserved as spare for future growth network traffic.

Next, the ring path was identified and defined by logically assigning nodes to a specific ring. Topological location of six other rings in same manner were defined and named access rings. Following this, the specifications of our proposed rings in terms ring type and bit rate was defined, and 2-Fiber Multiplex Section-Shared Protection Ring (2F-MSSPRing) - a type of SDH BLSR ring was selected.

IV. PROPOSED ALGORITHM

This algorithm is based on Constraints Satisfaction programming (CSP). It comprises three subroutines namely: Dimensioning, Ringassignment and Routing (DRR).

In order to fully understand how the algorithm works, we shall formerly discuss the SONET/SDH ring assignment problem instance.

A. Formal modeling of the problem

Let nnodes_i represents nodes assigned to access rings and is defined as X_{1i}

Let nnodes_j represents nodes assigned to federal ring and is defined as X_{2J}

At least 4 nodes are assigned to the federal ring:

$$\sum_j X_{2j} \ge 4 \tag{6}$$

Note that: $2j \ne 2 * j$

At most 1 nnodes$_i$ must be assigned to every access rings.

$$\sum_i X_{1i} \le 1 \tag{7}$$

Alternatively, it can be said that $X_i = 1$ if node$_{1i}$ is assigned to access ring k

Let nring$_k$ represents the access rings, and at instance t=0,

$$\sum_{k=1}^{6} nrings_{sk} \tag{8}$$

As $t \ge 1$, the number of access rings $nring_k \rightarrow 1$

Let $nring_f$ represents the federal ring, and at instance t=0,

$$\sum_f nring_f = 1 \tag{9}$$

When $t \ge 1$, the size of federal ring increases.

This phenomenon is described as ring merging and is further explained in section IVC. The traffic demand between any two nodes on the access rings is given as 4 units, and this is stated formally thus:

$$\sum_j X_{2jp} X_{2pj} = 4 \tag{10}$$

For uniform traffic demand, and

$$\sum_j X_{2jp} X_{2pj} = M \tag{11}$$

where $2 \le M \le 6$ for non-uniform traffic demand.

The expressions 6 to 11 and those that would be added in section IVC constitute the formal definitions of the important constraints considered in the design. Then, the objective function is therefore given as:

$$\text{Minimise } \sum_k nrings_k$$

B. Applying the DRR Algorithm

The heuristic is applied to five different network topologies whereby the number of rings are R=6, 5, 4, 3, and 2. For each topology, the network was populated with both uniform and non-uniform traffic demands. The resulting network topologies after reconfiguration for different number of rings with the same number of nodes and traffic demand are given as illustrated in Figure 7-9 below.

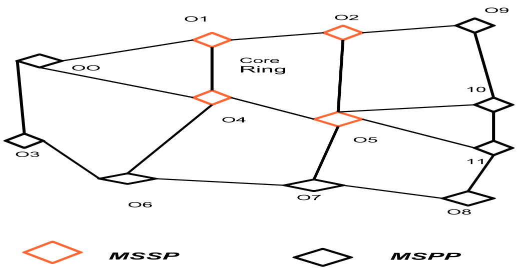


Fig. 7. The original network of 12 nodes and 7 rings before merging.

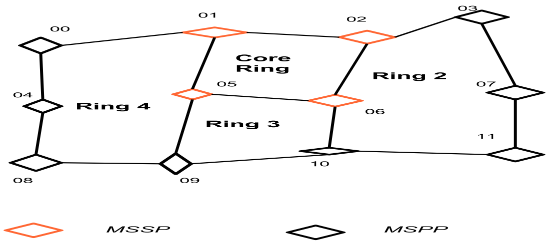


Fig. 8. Scenario 2: A network of 12 nodes and 4 rings.

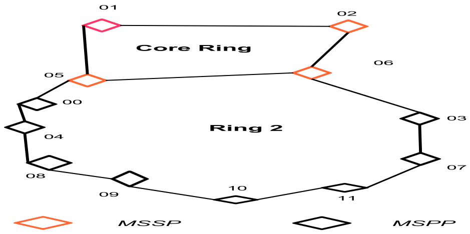


Fig. 9. Scenario 4: A network of 12 nodes and 2 rings.

An instant of the problem shows the inability of the original network (fig. 7) to accommodate a substantial amount of network traffic. We are then left with two possible options of either to stack the ring with rings of equal capacity or merge any two rings in the network in accordance to the implied constraint conditions in order that we may accommodate all the traffic demands. The process of merging means that nodes are assigned to rings such a manner that the total numbers of rings used in the network may be reduced.

During this process, all the inter-nodes distances were maintained and all the nodes were retained. The following variables: i.e. the number of rings “nring”, the number of nodes “nnodes” and the capacity of the rings, c^1_r are used in the algorithm. The input data to the algorithm are the network topology and the traffic demand to be served.

For a solution to be feasible, the algorithm must return within a solution that corresponds to a complete network traffic dimensioning, routing and ring assignment combination for the set of nodes/sites interconnection that represent the traffic demand to be satisfied over a specified network model.

The routing is implemented by ensuring that the total traffic over all rings are optimised; dimensioning is done without equipping any new fiber channel, and using a stack ring of the same capacity and bit rates as the original ring.

```
        Procedure: DRR (nnodes, nrings, $C_r$)
    begin:
        given:  Nnodes ∈ {$nnodes_i$ , $nnodes_j$} : nat,
                Nrings ∈ {$nring_f$ , $nrings_k$} : nat  B: real
      initialise:
       Nnodes ◄──── $y_{max}$ : start with max no of nodes
        Nrings ◄──── $y_{max}$ : start with max no of rings
            for each nnode ∈ Nnodes
             and for each nring ∈ Nrings;  do
               Ringdesign(Nnodes,Nrings) ◄──── $C_r$
            while
                ( I ring-nodes  I : > B) ; {
           Ringmerging(Nnodes,Nrings)
                }
                  if ( $Nrings_k$ =  1)  {
                     nnodes ◄──── ADM ;
                  } else if ($Nrings_k$ =2) {
              $nnodes_i$ ◄──── ADM plus DXC
                     } else if ($Nrings_k$ >3) {
                       $nnodes_f$ ◄──── MSSP
                  else
               Dimensioning (STM-N)
             Routing(optimised over all routes)
           Ringassignment(stacked, merge)
   end
```

Fig. 10. Algorithm for solving SONET/SDH Ring assignment problem.

Above is the proposed DRR algorithm for solving the ring-node assignment problem. DRR is the name of the procedure that calls Dimensioning, Routing and Ring assignment processes. *nnodes*, *nring* and c_r are the arguments; together they form arity of *DRR/3*. The total number of nodes *Nnod*es in the network is differentiated into two: $nnodes_i$, and $nodes_j$ and both are declared as natural number. Similarly, the total number of rings *Nrings* in the network is also differentiated into: the federal ring -$ring_f$ and the access ring -$rings_k$. Both are declared as natural number. The common bandwidth capacity is also declared as natural number and set to the value *B* Mbps.

We initialised both *Nnodes* and *Nrings* to maximum and commence the Ring design procedure. This subroutine (procedure) completes the ring design process by setting the ring capacity c_r to STM-4 2F-MSSPRing. Following this, is the test that verifies if the ring-nodes capacity is less than or equal to the value B. For all values of ring-nodes capacity greater than *B*, another subroutine Ringmerging is called. This process involves testing and assigning different nodes for each ring depending on the ring-node assignment. For any node connected to ONLY one ring, it must be configured as ADM back-to-back. Those that are connected between two distinct rings are also configured as ADM plus DXC, otherwise known as MSPP; while any nodes connecting three of more rings are configured as MSSP. All the nodes configured as MSSP, collectively form the backbone or federal ring.

Afterwards the algorithm proceeds by calling the Procedure DRR again and return.

V. SIMULATION RESULT

The simulation result in Figure 11 and 12 show the capability of the proposed DRR algorithm to return a solution in a ring assignment problem with the ultimate goal of reduced network cost. An instance of the problem where the algorithm is applied to two different network configurations with uniform and non-uniform traffic is considered.

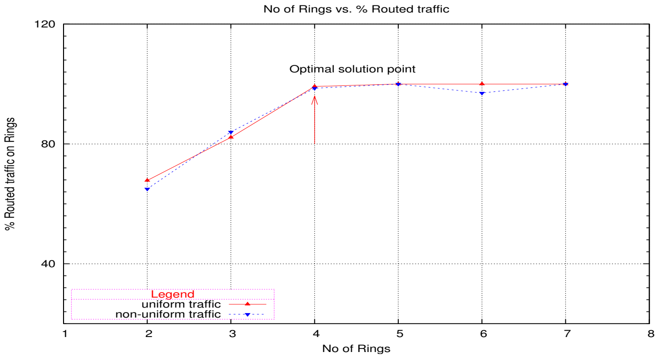


Fig. 11. Illustrates the use of DDR algorithm to solve ring assignment problem.

In both cases, an optimal solution that satisfies all the defined optical constraints was obtained at a point "Z" = (4, 98.9). Here the number of rings in the network is 4, and the percentage routed traffic is 98.9.

For the uniform traffic instance, the graph could be divided into two distinct parts. The first part is the linear region where the number of ring and total traffic capacity carried therein is directly proportional to the percentage of traffic routed in the network. The second part is depicted with a region that is almost nearly parallel to the horizontal axis (the "No of Rings" axis). At the point of discontinuity of the two parts are the optimal solution, and any attempt dimension the network to admit more traffic in the network beyond the critical point will yield little or no effect on the overall percentage of routed traffic in the network.

Fig.12 illustrates the case for that of non-uniform traffic. The traffic constitutes the bursty data traffic and is unpredictably erratic in characteristic as shown. On applying this traffic to our algorithm, it returns a solution at almost the same point as in the case of uniform traffic under the same optical constraints. Regrettably, the algorithm breakdown at any other point outside this critical point, and this may be possibly due to non-deterministic nature of the data (non-uniform) traffic. Adaptation of the algorithm to such type of traffic is left as an open issue to be considered in future work.

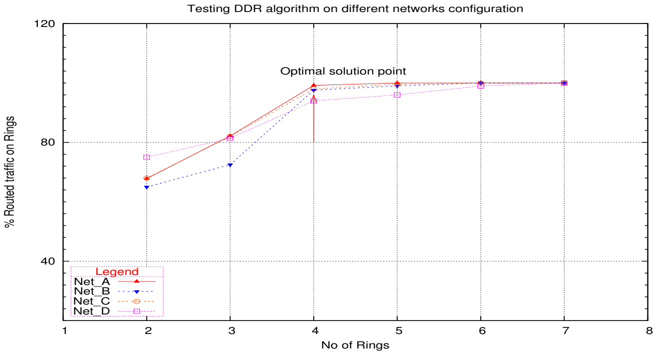


Fig. 12. Testing DDR algorithm for all-uniform traffic in different networks

Figure 12 depicts the percentage routed traffic demand that corresponds to the four investigated networks as a function of number of stacked rings. Each of the rings as shown composes of a number of stacked rings just sufficient enough to allow all the requested traffic demand to be completely routed in each of the network.

The % routed traffic increases linearly as the number of rings increases only to the maximum point, and then remained constant. At the point of optimal solution (as shown fig. 12), all the specified optical constraints are satisfied. Any increase in number of rings beyond this optimum value will have little or no effect on the total amount of traffic admitted to the network.

This shows that the DDR algorithm is "well-behaved" and therefore suitable for finding a solution to a ring assignment problem under uniform traffic demand.

A solution whereby the number of rings = 4 is a minimum solution that satisfies all the requirements and is therefore chosen as the optimum solution. Clearly, neither 2 nor 3 rings are feasible solution and are therefore rejected as candidate solutions. However, any number of rings greater than 4 though is equally a solution but will on the other hand incur high network cost.

VI. CONCLUSION

An alternative approach based on Constraints Satisfaction Programming (CSP) technology to solve ring assignment problem in multiservice, multiple constraints SDH optical networks design has been discussed. In this work, a heuristic algorithm was developed using the CSP technology to search for a network topology that provides an optimum solution in a wide area network (WAN). The solution does not only provide a low-cost design but also satisfies all constraints defined as users' and network requirements.

The study commences by extracting the generic constraints from the given users' and network requirements. Implied constraints were also generated, and together they form a set of inputs data to the proposed algorithm. The algorithm treated the network design process as graph partitioning problem and therefore attempts to find an optimal solution through searching method. In this process, procedure calls like ring assignment, network dimensioning and traffic routing were initiated. The call that returns a solution with minimum network cost, and that also satisfy the underlying constraints is chosen and considered optimum. The implementation of this algorithm was done in OPNET network simulator.

Even though, it is clear that the scheme is sufficient for finding solution(s) with minimal network cost, its efficiency is yet to be determined in terms of CPU time. The major problem lies in the difficulty of automating the process of transforming the constraints specifications to the format that could be easily represented in the supported programming language [10]. There is currently an ongoing research in this area.

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