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Traffic Flow Modeling of Data Networks and its Solution using Goal Programming

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Abstract— **Data transmission improvement over a network is vital for network performance and it can be enhanced if the traffic flow over the individual link of a network is maximized. Also the data network design with maximized traffic flow has become eminent with the growing demand for data networks. All these require that the traffic within the network should traverse as much as possible while satisfying certain criteria that depend on the methods adopted for increasing the data transmission. This paper presents the maximization of the traffic flow through the network links, where two objective functions have been fulfilled− (i) Optimization of the link utility, which in turn maximizes the link flow for a given link bandwidth and (ii) Optimization of the node utility that increases the node utilization by increasing the total traffic inflow. A model has been developed using these two objectives for selection of appropriate traffic through various links for a given network topology with a given traffic as the constraint criteria and the same has been solved using Goal Programming technique. It is a multi-objective optimization method that requires the priority assignment to different parameters and produces multiple optimal solutions from the feasible solution set. The elaborate description of the proposed optimization method is given, where a network example for the simulation of the proposed model is presented. The results so obtained are satisfactory and it is found that the proposed model is efficient and applicable to any network design problem for maximizing traffic flow of links and node utilization.**

Index Terms— **Network traffic flow assignment, Goal programming, Multi-objective optimization, Mathematical modeling.**

I. Introduction

THE traffic flow assignment problem is defined as allocation of traffic on different paths of a network such that the given network goal is optimized. To be more specific, given traffic requirement matrix, network topology, and capacity of links, the flow assignment problem finds optimal flow allocation through network links. In order to solve this problem, researchers have focused on the following three major approaches: (i) Simplex-based cutting plane methods, (ii) Lagrangian relaxation methods and (iii) Heuristic methods.

The simplex-based cutting plane methods have the advantage for improving their lower bounds through identification of new strong valid inequalities [1], whereas Lagrangian relaxation exploits the structure of the problem and facilitates heuristics design. Heuristic methods are used for solving very large networks. They have shown successful results when tailored to particular classes. But they often lack theoretical justifications and it is very difficult to assess their performance. Moreover, the objective function for flow assignment problems presented in the literature includes only single objective, which is to minimize either average network delay or total cost incurred.

In simplex-based cutting plane methods, the authors developed the capacitated network design problem having two types of facilities or values installed on the links and solved with mixed integer programming model [2]. The two facilities are low capacity having capacity *1* and high capacity having capacity value *C*. The problem is designed on an undirected graph but the flow is directed. The capacity constraints limit the total flow in both directions. The objective function minimizes the total cost incurred in loading all the facilities. A similar problem is studied by Bienstock *et al.* [3] with the exception that the authors considered flow costs and existing capacities. A cutting plane method was devised having similar valid inequalities as that of [2].

Lin and Yee [4] in Lagrangian relaxation methods had considered the routing and flow control problems in virtual circuit networks. The problem of choosing a path and adjusting the input rate for each source-destination of the network is solved. Three models were proposed and optimized. In the first model, the average number of packets and a throughput limitation cost are minimized. In the second model, allocation to the most poorly treated users is maximized and the third model is basically an extension of the second in which a constraint limiting the average number of packets was added. The emphasis of the paper was on developing near optimal algorithms for solving the three models using Lagrangian relaxation method. In [5], the authors proposed a Lagrangian relaxation technique for solving the minimum cost multicommodity flow problem as a sequence of single commodity flow problems. The objective function includes minimization of the aggregate cost of flow, where the constraints are based on the flow conservation for each commodity. The independent single commodity flow problems are coupled together by the bundle constraints that require capacity of a link must not be violated by the sum of flows of all commodities on that link.

In heuristic technique, a variety of genetic algorithm and evolutionary algorithm based approaches are used where bit-string and integer-string notations for chromosomes are considered, respectively [6, 7]. In [6], the objective function

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includes minimization of average delay and in [7], link topology and routing paths are optimized according to the costs so that average end-to-end packet delay does not exceed a specified value. An advanced representation was used in [8], where several cost factors are considered for optimization. A more advanced evolutionary algorithm has been proposed in [9]. The authors have developed an evolutionary algorithm having two levels. The "high" level applies typical evolutionary algorithm operators and the "low" level is based on the idea of a hierarchical algorithm. But their approach does not yield a classical hierarchical algorithm. As the objective, they have used Lost Flow in Node (LFN) function, which is a flow lost in any node of a network due to a failure of any single link. In [10], the authors proposed a genetic algorithm based model that uses GA-utilization as an indicator for effectiveness of the model, where the maximum allowable flow values for each link were restricted not to exceed 95% of the link capacity for avoiding congestion, and throughput of the network was not allowed to go below half of the sum of all links capacity. But any justification for taking such thresholds is not provided. The objective function includes minimization of average delay. The author in [11] has solved the flow assignment problem using three heuristic approaches. The first approach uses genetic algorithm, the second simulated annealing and the third, a hybrid technique of both algorithms. Here also the objective function contains average time delay of messages. Similarly, in [12, 13] single objective in the form of delay function has been considered as the optimization objective for solving flow assignment problems.

In this paper, the allocation of traffic flow on network links and its optimization have been done by considering two objective functions such as link utility and node utility rather than one as considered in the most of the related works published so far. In this regard, an optimization technique, called Goal Programming approach is used to model, formulate and solve for traffic flow optimization of the computer networks. It may be noted that the method takes into account the objectives of the problem simultaneously and chooses the most satisfactory solution from the set of feasible solutions [14]. Although this technique is generally used for optimization of OR problems, in the present work, the method has been used for the traffic flow optimization of computer networks.

The rest of the paper is organized in the following manner. Section 2 depicts the problem formulation, which includes objective functions and corresponding constraints, and its Goal Programming modeling. In section 3 the solution methodology is provided with a network example. Section 4 explains the results and finally section 5 concludes the paper.

II. Multi-objective Traffic Flow Optimization using Goal Programming

In this section, the problem of finding appropriate link traffic flow for a given network and traffic is addressed. As stated, a multi-objective model using two objective functions namely link utilization and the node utilization by increasing in-flow traffic to a node is defined and formulated. It is then solved using an optimization technique known as Goal Programming method. It analyzes the objective functions and provides fairness to the traffic flow allocation problem through the satisfaction of the constraints supplied. It actually takes into account all the objectives of a problem simultaneously and chooses the most satisfactory solution from the set of feasible solutions [14].

A. Problem Description and Modeling

A network consists of two primary attributes namely nodes and links, both having their own sets of characteristics. One of the main characteristics of a node is its processing rate, which in turn defines the node throughput that is always lesser than the processing capacity. For a given traffic, all the nodes of a network do not share the traffic equally and thus, the different nodes produce different throughput although the processing capacity of all the nodes may be the same. Here, we propose the maximization of the node throughput so that the node utilization can be increased. On the other hand, the network links are characterized by real-life traffic flow and capacity. The traffic flow over a given link means the amount of information transmitted through it while the capacity is the measure of highest quantity of information that can be transmitted per unit time. The flow of a link depends on the traffic between the network node pairs as well as on traffic of the whole network. In this section, the flow assignment problem has been modeled to assign the proper traffic to each link so that the link utilization, similar to the node utilization, is also enhanced. The problem formulation is given below:

- **Objective Functions and Constraints**

1. *Link utilization:* It is defined as the ratio of the actual traffic flow to the bandwidth of a link *(i, j)*, where both of them are expressed in terms of bits per second (bps). Our main objective is to maximize the actual traffic flow through a link such that the full bandwidth of it is utilized and the network throughput is increased. Thus, if x_{ij} and C_{ij} are the traffic flow and the link bandwidth respectively, then we have the utilization of a link as
$u_{ij} = \frac{x_{ij}}{C_{ij}}$, where u_{ij} is the utilization of the link *(i, j)*
The summation of all links' utilization U (say) can be expressed as
$$U = \sum_{ij \in E} \frac{x_{ij}}{C_{ij}}$$, where $i \neq j$ and E is the set of all links of a network
The purpose of the objective function is to
$$\text{Maximize} \quad U = \sum_{ij \in E} \frac{x_{ij}}{C_{ij}}$$
Subject to the following constraints
$x_{ij} \leq C_{ij}$, where total traffic and the network topology are remained same

2. *Node utilization:* It is defined as the ratio of the total inflow traffic to a node to the processing rate of a network node, where the unit used for both of them is bps. The main objective of this function is that the processing rate of a node may be underutilized if the total traffic toward a node is lesser than its processing

capability, and thus the network performance is degraded. Here we propose to enhance the node utilization by increasing the traffic flow within the constraints of fixed traffic for a given network topology. If T_i is the processing rate of a node, then the node utilization v_j can be written as

$v_j = \frac{\sum_{ij \in E_j} x_{ij}}{T_j}$, where E_j is set of links to a node j, i.e., x_{ij} is the traffic flows from node i to a node j.

The summation of the utilizations V (say) of all nodes is $V = \sum_j v_j$

The purpose of this objective function is to

Maximize $V = \sum_j v_j$

Subject to the following constraints

(i) $\sum_{ij \in E} x_{ij} = X$, where $i \neq j$ and X is total fixed traffic or load of a network

(ii) $\sum_{ij \in E_j} x_{ij} \leq T_j$

The above problem formulation is modelled in a versatile method using Goal Programming which is detailed next.

B. *Goal Programming Model Formulation*

This section presents a Goal Programming model for optimizing the traffic flow through the network links and increasing the node utilization. The Goal Programming is a satisfying procedure that attempts to achieve a satisfactory level of multiple objectives rather than the best possible outcome for a single objective. It minimizes the deviations between what can be actually achieved and the goals set for the objectives. For the case where the concerned goal surpasses the set goal values, the deviation is positive. On the other hand, if there is an underachievement of goal, then there will be a negative deviation. In a typical situation, the set goals can be achieved only at the expense of other goals. So, it is necessary to establish a hierarchy of importance, i.e., priority among these goals such that lower priority goals are tackled only after higher priority goals are achieved. Also it is not possible to achieve every goal, and in that case Goal Programming attempts to reach the results of satisfactory level for multiple objectives.

The Goal Programming model for the proposed network traffic flow optimization and the node utilization as well is given as follows:

$$Minimize\ Z = \sum P_k(d_i^-,\ d_i^+)$$

Subject to,

$$f_i(x) + d_i^- - d_i^+ = a_i$$

$$x, d_i^-,\ d_i^+ \geq 0$$

$$f_i(x) = \begin{cases} \sum_{(i,j) \in E} \frac{x_{ij}}{C_{ij}} \\ \frac{\sum_{ij \in E_j} x_{ij}}{T_j} \\ \frac{x_{ij}}{\sum_{ij \in E} x_{ij}} \\ \sum_{ij \in E_j} x_{ij} \end{cases}$$

where $P_k(d_i^-,\ d_i^+)$ is a linear function of the deviational variables, P_k is the k^{th} preemptive priority level and a_i is the value of the aspiration level associated with objective $f_i(x)$. Note that the variables d_i^- and d_i^+ are the negative and positive deviations of the objectives from their aspiration levels, respectively. The proposed model has been illustrated with the help of an example given in the next section.

III. Solution Methodology with Numerical Example

An example network having four nodes and five links given in the adjacency matrix in table 1 is considered for the Goal modelling, solving and the simulation of the proposed model.

TABLE I
ADJACENCY MATRIX OF THE NETWORK

Nodes	**1**	**2**	**3**	**4**
1	0	1	1	0
2	1	0	1	1
0	1	1	0	1
4	0	1	1	0

A. *Notations Used*

The notations used in the model for the different decision variables, deviational variables and the right hand side values of the goal constraint equations are presented in the tables 2-3 respectively.

B. *Solution Methodology*

The goal constraints, which include the objective functions and the constraints for the concerned network, are explained below:

1. *Link Utilization:* The under-achievement of link utilization (d_1^-) is to be minimized while its over-achievement (d_1^+) is allowed.

$$\sum_{ij \in E} \frac{x_{ij}}{C_{ij}} - d_1^+ + d_1^- = a_1$$

i.e.

$$\frac{x_{12}}{C_{12}} + \frac{x_{13}}{C_{13}} + \frac{x_{23}}{C_{23}} + \frac{x_{24}}{C_{24}} + \frac{x_{34}}{C_{34}} - d_1^+ + d_1^- = a_1 \quad (1)$$

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2. *Node Utilization:* The under-achievement of node utilization (d_2^-) is to be minimized while its over-achievement (d_2^+) is allowed.

$$\sum_{j=1}^{4} v_j - d_2^+ + d_2^- = a_2$$

i.e.

$$\frac{x_{12} + x_{13}}{T_1} + \frac{x_{12} + x_{23} + x_{24}}{T_2} + \frac{x_{13} + x_{23} + x_{34}}{T_3} + \frac{x_{24} + x_{34}}{T_4} - d_2^+ + d_2^- = a_2$$

i.e.

$$\frac{2}{T}(x_{12} + x_{13} + x_{23} + x_{24} + x_{34}) - d_2^+ + d_2^- = a_2 \quad (2)$$

3. *Flow Conservation:* Both the over-achievement as well as the under-achievement are to be minimized.

$$x_{12} + x_{13} + x_{23} + x_{24} + x_{34} - d_3^+ + d_3^- = a_3 \quad (3)$$

4. *Bandwidth of link (1,2):* The over-achievement of link bandwidth (d_4^+) is to be minimized while its under-achievement (d_4^-) is allowed.

$$x_{12} - d_4^+ + d_4^- = a_4 \quad (4)$$

5. *Bandwidth of link (1,3):* The over-achievement of link bandwidth (d_5^+) is to be minimized while its under-achievement (d_5^-) is allowed.

$$x_{13} - d_5^+ + d_5^- = a_5 \quad (5)$$

6. *Bandwidth of link (2,3):* The over-achievement of link bandwidth (d_6^+) is to be minimized while its under-achievement (d_6^-) is allowed.

$$x_{23} - d_6^+ + d_6^- = a_6 \quad (6)$$

7. *Bandwidth of link (2,4):* The over-achievement of link bandwidth (d_7^+) is to be minimized while its under-achievement (d_7^-) is allowed.

$$x_{24} - d_7^+ + d_7^- = a_7 \quad (7)$$

8. *Bandwidth of link (3,4):* The over-achievement of link bandwidth (d_8^+) is to be minimized while its under-achievement (d_8^-) is allowed.

$$x_{34} - d_8^+ + d_8^- = a_8 \quad (8)$$

9. *Processing rate of node 1:* The over-achievement of node 1's processing rate (d_9^+) is to be minimized while its under-achievement (d_9^-) is allowed.

$$x_{12} + x_{13} - d_9^+ + d_9^- = a_9 \quad (9)$$

10. *Processing rate of node 2:* The over-achievement of node 2's processing rate (d_{10}^+) is to be minimized while its under-achievement (d_{10}^-) is allowed.

$$x_{12} + x_{23} + x_{24} - d_{10}^+ + d_{10}^- = a_{10} \quad (10)$$

11. *Processing rate of node 3:* The over-achievement of node 3's processing rate (d_{11}^+) is to be minimized while its under-achievement (d_{11}^-) is allowed.

$$x_{13} + x_{23} + x_{34} - d_{11}^+ + d_{11}^- = a_{11} \quad (11)$$

12. *Processing rate of node 4:* The over-achievement of node 4's processing rate (d_{12}^+) is to be minimized while its under-achievement (d_{12}^-) is allowed.

$$x_{24} + x_{34} - d_{12}^+ + d_{12}^- = a_{12} \quad (12)$$

The Goal Programming model includes a number of objective functions, all of which are not treated as equally important. However, it is necessary to assign preemptive priorities to the objectives, where the priorities in descending order are indicated by P_1, P_2, P_3 and so on. It is also necessary to assign weights to each objective such that the positive numbers are used as weights that reflect the importance associated with the minimization of a deviational variable assigned to a given objective [14]. The

TABLE II
NOTATIONS USED FOR DECISION VARIABLES

Name of the decision variables	Notations
Traffic flow through link (1,2)	x_{12}
Traffic flow through link (1,3)	x_{13}
Traffic flow through link (2,3)	x_{23}
Traffic flow through link (2,4)	x_{24}
Traffic flow through link (3,4)	x_{34}

TABLE III
NOTATIONS USED FOR DEVIATIONAL VARIABLES AND RIGHT HAND SIDE VALUES

Notation for deviational variables	Name of the goal constraints	Notation for R.H.S. values
d_1^+, d_1^-	Link Utilization	a_1
d_2^+, d_2^-	Node Utilization	a_2
d_3^+, d_3^-	Flow Conservation	a_3
d_4^+, d_4^-	Bandwidth of link (1,2)	a_4
d_5^+, d_5^-	Bandwidth of link (1,3)	a_5
d_6^+, d_6^-	Bandwidth of link (2,3)	a_6
d_7^+, d_7^-	Bandwidth of link (2,4)	a_7
d_8^+, d_8^-	Bandwidth of link (3,4)	a_8
d_9^+, d_9^-	Processing rate of node 1	a_9
d_{10}^+, d_{10}^-	Processing rate of node 2	a_{10}
d_{11}^+, d_{11}^-	Processing rate of node 3	a_{11}
d_{12}^+, d_{12}^-	Processing rate of node 4	a_{12}

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TABLE IV
ASSIGNMENT OF PRIORITIES AND WEIGHTS

Name of the goal constraint	Priority	Weight
Link Utilization	P_1	1
Node Utilization	P_1	1
Flow Conservation	P_2	1
Bandwidth for all links	P_2	1
Processing rate of all nodes	P_3	1

priorities and weights that have been assigned to various objectives of the Goal Programming model for our example network are presented in table 4, where equal weight equal to *1* is used for equal treatment of the deviational variables.

The objective function of the Goal model as given below consists of the deviational variables whose under-achievements and over-achievements are to be minimized.

$$Minimize\ Z = P_1(d_1^- + d_2^-) + P_2(d_3^+ + d_3^- + d_4^+ + d_5^+ + d_6^+ + d_7^+ + d_8^+) + P_3(d_9^+ + d_{10}^+ + d_{11}^+ + d_{12}^+)$$

With the following $Goal\ Constraints$:

1. $\frac{x_{12}}{C_{12}} + \frac{x_{13}}{C_{13}} + \frac{x_{23}}{C_{23}} + \frac{x_{24}}{C_{24}} + \frac{x_{34}}{C_{34}} - d_1^+ + d_1^- = a_1$
2. $\frac{2}{T}(x_{12} + x_{13} + x_{23} + x_{24} + x_{34}) - d_2^+ + d_2^- = a_2$
3. $x_{12} + x_{13} + x_{23} + x_{24} + x_{34} - d_3^+ + d_3^- = a_3$
4. $x_{12} - d_4^+ + d_4^- = a_4$
5. $x_{13} - d_5^+ + d_5^- = a_5$
6. $x_{23} - d_6^+ + d_6^- = a_6$
7. $x_{24} - d_7^+ + d_7^- = a_7$
8. $x_{34} - d_8^+ + d_8^- = a_8$
9. $x_{12} + x_{13} - d_9^+ + d_9^- = a_9$
10. $x_{12} + x_{23} + x_{24} - d_{10}^+\ d_{10}^- = a_{10}$
11. $x_{13} + x_{23} + x_{34} - d_{11}^+ + d_{11}^- = a_{11}$
12. $x_{24} + x_{34} - d_{12}^+ + d_{12}^- = a_{12}$

$Subject\ to,$

$x_{ij}, d_k^+, d_k^- \geq 0$, where $(i, j) \in E$ and $1 \leq k \leq 12$

IV. Results and Discussion

The input values for different parameters of the example network used in the Goal Programming model are given as follows: Link bandwidths– *(1-2)*: 96 bps, *(1-3): 200 bps*, *(2-3): 128 bps*, *(2-4):160 bps* and *(3-4): 182 bps*. Node processing rates- There are 4 nodes in our example network, the processing rates of which are assumed to be equal to *112 bps*. Network traffic- A fixed traffic equal to *200 bps* is considered. Goal thresholds (aspirations)- For link utilization: *5* and node utilization: *4*. Based on the above input values, a set of alternative optimized values for link traffic flow and node utilization have been found, and one of them for appropriate traffic selection is given in table 5. It is seen from table 5 that no traffic is selected for link *(3-4)* and the reasons for this are that the first two priorities out of three priorities, corresponding to the *link utilization and the node utilization*, and the *flow conservation and bandwidth*

TABLE V
OPTIMAL TRAFFIC VALUES FOR EACH LINK (DECISION VARIABLES)

Traffics (Decision Variables)	Optimal or appropriate Traffic Values in bps
x_{12}	24.0000
x_{13}	88.0000
x_{23}	24.0000
x_{24}	64.0000
x_{34}	0.0000

constraints have been satisfied and the total given traffic *200 bps* have been completely allotted to other four links. The simulation results for node utilization are given in table 6.

TABLE VI
NODE UTILIZATION

Nodes	Total traffic to a node in bps	Node Utilization
Node-1	$x_{12} + x_{13} = 24 + 88 = 112$	100%
Node-2	$x_{12} + x_{23} + x_{24} = 24 + 24 + 64 = 112$	100%
Node-3	$x_{13} + x_{23} + x_{34} = 88 + 24 = 112$	100%
Node-4	$x_{24} + x_{34} = 64 + 0 = 64$	57%

Note that the utilization of all nodes except the node-*4* is *100%*. The node-*4* has *57%* utilization and the reason is that no traffic to the link *(3-4),* which is connected to the node-*4*, has been given during the selection of the appropriate traffic to different links as shown in table 5. As the proposed technique uses Goal Programming for problem formulation and solution, hence any network can be formulated in this model and the results obtained will be optimized. This is because Goal Programming is a multi-objective optimization technique that achieves a satisfactory level for all the objectives based on the constraints and priorities.

V. Conclusion

With respect to data networks the problem of data flow optimization in various links is very crucial for increasing network performance. The enhancement of node utilization that depends on the data flow optimization is also important for increasing the network throughput. In this paper an attempt has been made to model and solve using a multi-objective technique called Goal Programming for achieving link and node utilization targets. In this regard, an example network is considered, which has been simulated and optimized by multi-objective Goal Programming technique. The results obtained show that it effectively assigns traffic to different links and enhances the node utilization. We used the priority order– *link and node utilization*, *flow conservation and bandwidth constant*, and *node processing rate* in descending fashion during our simulation and obtained the corresponding results as shown in section 4. The Goal Programming technique requires the users to specify a priority order to get the results accordingly.

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