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COMMUNICATION NETWORK DESIGN PROBLEMS USING THE FUZZY SET APPROACH

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ABSTRACT: In this study, we newly formulated the link capcity alocation problem and the link capacity allocation and routing problem in an voice/data integrated network by the fuzzy set concept. We developed efficient algorithms for the above fuzzified problems and successfully showed that the fuzzy set theory is the powerful tool for the design problems in communication networks.

1.Introduction

This paper deals with the problems which are important design issues for an integrated voice/data digital network. One is the problem of allocating time slots between voice and data traffic at each link in integrated network. The other is the extended problem of allocating time slots between voice and data traffic at each link and simultaneously determining routes for each traffic.

One of the major difficulties in the analysis of the integrated system comes from the different characteristics of voice and data traffic. They require different performance criteria: blocking probability for voice and average network delay for data. Moreover, the two criteria are even conflicting in the sense that if more capacity is allocated to voice, its blocking probability decreases while the average delay of data increases, and vice versa.

The goal of the problems may be generally stated as to utilize the scarce resource, the transmission capacities, in an effective manner while guaranteeing a satisfactory level of the performance measure for each type of traffic. The common starategy for achieving this goal in the literature is to optimize one performance measure with the performance requirement of the other measure as a constraint as shown in the studies of Avellaneda et al., Li et al. and Woodside. However, this way of handling the performance of one type of traffic by imposing a rigid constraint does not fully take into account flexible real-world situations. The designer of a network may not be happy only with the prespecified performance level of the traffic satisfied, but wants further to improve its performance as much as possible. Or he may think that the minimum tolerable performance level is not as rigid as specified in the constraint, i.e., he may go along with its performance level lower than the prespecified level in some senses. Also when the problem has conflicting objectives as the two performance criteria here, one becomes interested in finding an efficient solution which optimally trades off the conflicting objectives. If the above approach is taken for this purpose, there is no other way but resort to a complex iterative procedure by changing the tightness levels of the constraints, say the prespecified perfoermance levels in our problems.

Motivated by this observation, the capacity assignment problem, and the capacity and flow assignment problem are formulated as multiobjective optimization models, which seek to achieve both perfermance criteria at their highest possible values. Principal to multiobjective optimization is the concept of "efficient solution", where any improvement of one objective can be achieved only at the expense of another. In multiobjective optimization, one is especially interested in singling out, from the set of efficient solutions, that efficient solution which qualifies as a best compromise from the design maker's point of view. The primary aim of this paper is to identify such "efficient" allocation and routing whereby the blocking probalility for voice and the average delay for data are optimally traded off. Among several known approaches, we shall employ the fuzzy set-theoritic approach mainly because of its simple but effective way of handling the imprecise nature of the decision maker's judgement.

Fuzzy set theory, which was first introduced in 1965 by Zadeh, has become accepted in the literatureas a tool for dealing with certain forms of imprecision that frequently occur in decision making environments, but for which the probability calculus is inadequate. Such imprecision is inherent in multiobjective environments where the decision maker's preferences over various alternatives are not known precisely. Many design and control problems in communication systems are indeed well suited for the analysis using fuzzy sets, due to their characteristics of having multiple performance criteria, some of whic are often conflicting. In this respect, it is rather surprising to find that fuzzy sets have not, or little if any, been used for the studies in communication betwork systems. Another contribution of this study may be, besides providing an efficient compromise allocation of trunk capacities, and an efficient compromise allocation and routing in a voice/data integrated network, in shedding light on the potential of fuzzy set theory as a powerful vehicle for the analysis of those communication systems with multiple performance criteria.

The fuzzy set method proposed here will be implemented for the fixed boundary multiplexing system. The method can, in principle, be applied to the movable boundary system too. However, it will not be addressed here, owing to the complexities including the so-called voice correlation effect. Though the basic framework of this bandwidth allocation problem is taken from the work by Avllaneda et al..

2. Biobjective Models

2.1. Capacity Assignment Problem

A number of studies have been published on how efficiently to integrate diffemt types of traffic on shared links in an integrated network. Of particular interest for us is the work by Avellaneda et al., which presents a compact formulation of the problem. With the reasons and motivations provided in the introduction, the capacity allocation probelm in an integrated network is formulated in this paper as the following biobjective optimization model:

$$\text{Minimize} \quad \begin{pmatrix} T(V) \\ P(V) \end{pmatrix},$$
$$\text{Subject to} \quad m_i \leqslant V_i \leqslant M_i, \quad i = 1, \ldots, L$$

where T(V) denotes the average network delay, P(V) denotes the average blocking probability, V_i is the number of slots allocated for voice on link i, and the vector $V=(V_1,\ldots,V_L)$ then defines an allocation. Also m_i denotes the minimum number of slots reserved for voice, and $(N - M_i)$ denotes the minimum number of slots reserved for data.

Under the simplest membership functions of linear form for average network delay for data and average blocking probability, the "fuzzy" version the above biobjective model as follows(FCAP):

$$\text{Maximize} \quad \{\min(\mu_D(V), \mu_V(V))\},$$
$$\text{Subject to} \quad m_i \leqslant V_i \leqslant M_i, \quad i = 1, \ldots, L$$

where

$$\mu_D(V) = 1 + \frac{T^0}{d^t} - \frac{1}{d^t}\left[\sum_{i=1}^{L} \frac{\lambda_i T_i(V_i)}{\gamma}\right]$$

$$\mu_V(V) = 1 + \frac{P^0}{d^p} - \frac{1}{d^p}\left[\sum_{i=1}^{L} \frac{\beta_i P_i(V_i)}{\alpha}\right]$$

2.2. Capacity Assignment and Routing Problem

This problem is just extended problem of the Capacity assignment problem which includes the routing for each types of traffic as well as the allocation of link capacity. But this problem is much more heavier than the capacity allocation problem.

With the same assumptions used in section 2.1 and some assumptions, the "fuzzy" biobjective model of this problem as follows(FCFAP):

$$\begin{aligned}
\text{Max} \quad & \min\{\mu_T(V,F), \mu_P(V,F)\} \\
\text{s.t.} \quad & \sum_{n=1}^{N_k} X(k;n) = R_k, \quad \forall k \\
& \sum_{k=1}^{Q}\sum_{n=1}^{N_k} X(k;n)P(k;n) = F \\
& F_i \le \frac{N - V_i}{N} C, \quad i = 1, \cdots, L \\
& \sum_{n=1}^{\bar{N}_k} \bar{X}(k;n) = \bar{R}_k, \quad \forall k \\
& \sum_{k=1}^{Q}\sum_{n=1}^{\bar{N}_k} \bar{X}(k;n)\bar{P}(k;n) = \bar{F} \\
& \bar{F}_i \le V_i, \quad i = 1, \cdots, L \\
& m_i \le V_i \le M_i, \quad i = 1, \cdots, L \\
& X, \bar{X}, F, \bar{F} \ge 0
\end{aligned}$$

3. Solution Methods

3.1. Solution method for FCAP

We developed the following incremental algorithm due to Fox for the fuzzified link-by-link bandwidth allocation problem(FCAP).

Incremental Algorithm

Step 0 (Initialization):
1. Start with the initial allocation $V^{(0)} = m$.
2. Initialize the index set $S = \{1, \ldots, L\}$.

Step $k\,(k = 1, 2, \ldots)$:
1. Let $V^{(k)} = V^{(k-1)} + e_i$, where e_i is the ith unit

vector and i is any index in S which attains

$$\max_{j\in S}\left\{\frac{f_j\left(V_j^{(k-1)}\right)-f_j\left(V_j^{(k-1)}+1\right)}{g_j\left(V_j^{(k-1)}+1\right)-g_j\left(V_j^{(k-1)}\right)}\right\}.$$

2. If $\mu_V(V^{(k)}) \geqslant \mu_D(V^{(k)})$, either $V^{(k-1)}$ or $V^{(k)}$, which corresponds to $\min\{\mu_V(V^{(k-1)}), \mu_D(V^{(k)})\}$, is our solution. And terminate.
3. If $V_i^{(k)} \geqslant M_i$, drop the index i from the candidate set S for further consideration.
4. Go to Step $k+1$.

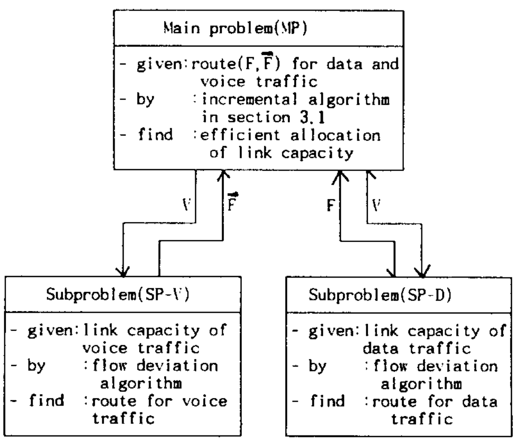
3.2. Solution method for FCFAP

FCFAP become a very large problem and there is no direct solution method for this problem. Therefore we decomposed it into one main problem(MP) and two subproblems(SP-D, SP-V), and found the heuristic solution by solving iteratively the three problems.

$$(MP)\quad \begin{array}{ll} \text{Max} & \min\{\mu_T(V), \mu_P(V)\} \\ \text{s.t.} & m_i \le V_i \le M_i, \quad i = 1, \cdots, L \end{array}$$

$$(SP\text{-}V)\quad \begin{array}{ll} \text{Min} & P(\bar{F}) \\ \text{s.t.} & \sum_{n=1}^{\bar{N}_k} \bar{X}(k;n) = \bar{R}_k, \quad \forall k \\ & \sum_{k=1}^{Q}\sum_{n=1}^{\bar{N}_k} \bar{X}(k;n)\bar{P}(k;n) = \bar{F} \\ & \bar{F}_i \le V_i \\ & \bar{X}, \bar{F} \ge 0 \end{array}$$

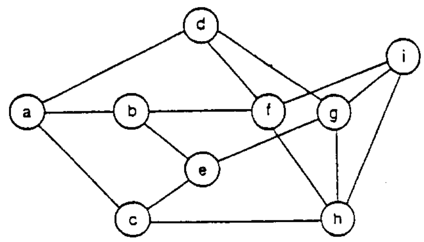
$$(SP\text{-}D)\quad \begin{array}{ll} \text{Min} & T(F) \\ \text{s.t.} & \sum_{n=1}^{N_k} X(k;n) = R_k, \quad \forall k \\ & \sum_{k=1}^{Q}\sum_{n=1}^{N_k} X(k;n)P(k;n) = F \\ & F_i \le \frac{N - V_i}{N} C, \quad i = 1, \cdots, L \\ & X, F \ge 0 \end{array}$$



(figure-1) relationship between MP, SP-D, and SP-V

4.Test Examples and Conclusion

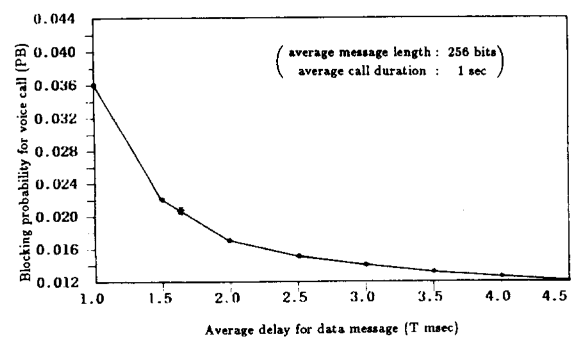
Consider an integrated network consisting of 9 nodes and 15 links as shown figure-2. Each link of the network is assumed to have a capacity of 1.544 Mbps in each direction. And each frame consists of 24 8-bits bytes. Traffic matrix were generated in a similar manner in Avellaneda's study(table-1). The average message length is 256 bits and the results are shown in figure-3 and table-2.



(figure-2) example network

Link i	L_i(messages/s)	β_i(calls/s)	(m_i, M_i)
1(ab)	1200	13	(7,18)
2(ac)	1050	12	(7,18)
3(ad)	1270	14	(7,18)
4(be)	940	10	(7,18)
5(bf)	1060	11	(7,18)
6(ce)	1310	15	(7,18)
7(ch)	1240	14	(7,18)
8(df)	1170	11	(7,18)
9(dg)	1340	15	(7,18)
10(eg)	1320	14	(7,18)
11(fh)	1350	15	(7,18)
12(fi)	960	12	(7,18)
13(gh)	1160	11	(7,18)
14(gi)	1270	14	(7,18)
15(hi)	1290	14	(7,18)

(table-1) summary of traffic matrix



(figure-3) comparision of conventional solution and fuzzy solution

	T(ms)	PB	Time [a]
Solutions by the conventional method	1.0	0.036	99
	1.5	0.022	135
	2.0	0.017	159
	2.5	0.015	166
	3.0	0.014	171
	3.5	0.013	174
	4.0	0.013	177
	4.5	0.012	180
Ours	1.688	0.021	175

[a] CPU time in milliseconds on CYBER 174-835 excluding I/O time.

(table-2) Computational results

Throughout this study, relative priority has been given to emphasizing the suitability of the fuzzy approach in our multi-criteria communication desig problems. It is hoped that this study serves as one successful illustration for demonstrating the potential of fuzzy set theory as a powerful tool for analysis of communication systems with multiple criteria.

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