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Decision models for designing and planning private communication networks

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Abstract

We consider the recently developed reconfigurable digital data networks consisting of T1/T3 circuits and Digital Crossconnect Systems (DCSs). A DCS is a device to patch base channels electronically from one T1/T3 circuit to another with a negligible queuing delay at the connecting node. We present new decision models for the design and circuit leasing policies of such digital backbone networks. Our model takes advantage of the special capabilities of the DCS technology and is likely to result in remarkable economic gains for the private network users. The formulation and analyses presented here simultaneously address the following problems: physical link and capacity selection, logical network configuration and channel assignment, and traffic routing on the logical network. The problem formulation results in a large-scale non-linear mixed integer program, and we propose an efficient solution methodology employing Lagrangean relaxation and subgradient optimization. Several numerical results illustrate the utility of our approach for these complex problems. We show that the economies of scale built into the tariff structure of these digital networks can be successfully exploited, and that the inherent flexibility of DCSs leads to logical networks that are dramatically different from their underlying physical topologies.

Keywords: Private networks; Data networks; Communication networks; Digital crossconnect systems; Reconfigurable networks; Topology design; Decision support systems

1. Introduction

In a world of dynamic markets and global competition, corporations need to be highly flexible in order to capture rapidly changing opportunities. To meet this challenge, "just-in-time" partnerships of independent companies that bring their respective core competencies together to meet a specific market opportunity have emerged; partnerships of this nature are now referred to as virtual corporations. This new business model requires an efficient global telecommunication infrastructure to provide information exchange capabilities to every participant. For example, an American design firm must be able to exchange engineering drawings and specifications with an Asian manufacturer in real time and in a transparent manner. This global telecommunication infrastructure may be established either by relying on public networks or by building a private network. Public networks have largely been unable to deliver the kind of services a virtual corporation would need: that is, (a) the band-

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other hand, another important cost involved in telecommunication networks, often overlooked, is the users' delay cost due to traffic congestion. This cost may include an opportunity cost, the cost of lost goodwill, etc. [8]. Network designers thus tend to maintain low utilization of communication circuits by providing circuits with ample bandwidth. Network managers are faced with the tradeoff between the cost of delay and the cost of leasing added capacity for their circuits. Finding the optimal tradeoff point between these two cost components is an important decision problem and has been addressed in several papers [15,20,25,29].

Our paper extends previous studies by viewing modern data networks, such as packet-switched networks, as *logical networks* over a reconfigurable private network of T1/T3 circuits. Traditional topology design [2,5,16,27] and capacity and flow assignment [15,25,26] studies solve a static network case, ignoring the reconfigurability of private networks. This reconfigurability based on DCSs implies that the capacity of a link between a pair of packet switches – in terms of the number of DS-0 channels – can be expanded without leasing additional circuits to meet increased traffic volume on that link. Traditional topological design problems determine the minimum cost topology of a network, with the capacities of candidate links given and fixed. Capacity and flow assignment problems strive to determine the link capacities and the routing policy in an optimal way. Following the link costs used by those studies will overlook the fact that the bandwidths in our T1/T3 networks are bought in bulk (i.e., in the form of batches of T1s or T3s) and the marginal cost of link capacity is thus sometimes zero. Thus using traditional topological design or capacity and flow assignment studies for DCS networks will result in sub-optimal performance.

Several papers have also been published on the design of reconfigurable networks. Monteiro and Gerla [23] address the topological reconfiguration of an Asynchronous Transfer Mode (ATM) network embedded in a backbone facility network using DCSs. They conclude that reconfigurability substantially reduces traffic congestion. Doverspike and Jha [9] use data from Bellcore to show that network capacity can be reduced by 14% using reconfigurable DCS networks as compared with conventional hierarchical routing. Lee and Yee [22] solve the joint optimization of the logical network topology design and capacity assignment problems for reconfigurable data networks. By minimizing the average delay of a packet, they model this problem using non-linear integer programming. These papers, however, assume that the physical topology and the link capacities are given. Chari and Dutta [3,4] model the private backbone network design problem without exploiting the economies of scale in the lease cost structure of digital circuits.

Our paper is the first to integrate the topological design and physical link capacity allocation problems with traffic routing for a reconfigurable network. This integration takes advantage of the special capabilities of the recently developed DCS technologies and is likely to result in remarkable economic savings for the users. Our model also captures the predominant features of this technology: we explicitly acknowledge that the capacity of the physical links is discrete in the multiple of 24 DS-0 channels (one T1), and that there are economies of scale in leasing T1 or T3 circuits. Modelling the details of these decision problems leads to a large-scale mixed integer program. We provide a novel Lagrangean relaxation method for computing lower bounds and heuristics leading to feasible solutions which are very close to optimal.

The next section provides a formulation for the decision model and outlines the solution procedure. Section 3 presents the results of several numerical experiments. The final section offers a summary and concluding analysis.

2. Formulation of the decision model

The decision model presented in this section determines the topology of a private network of T1/T3 circuits – the *physical network* – and the type (or quantity) of circuits (e.g., null, one T1, two T1s, etc.) for each of the network's candidate links. A "null" implies that the network topology will not include this physical link.

ADEC, AEBC, AEDC, ABEDC, ABDEC, ADBEC, ADEBC, AEBDC, AEDBC}. R_l^L is defined as the set of l-routes that use $l \in L$. For example, R_{AB}^L = {AB, BAC, ABDC, ABEC, ABD, ABCD, ABED, ABE, ABCE, ABDE, BAC, BADC, BAEC, BAD, BACD, BAED, BAE, BACE, BADE, CABD, CBAD, CABE, CBAE, DABE, DBAE}.

Other index sets and parameters used in the model are the following:

T_p: the set of possible circuit types for physical link $p \in P$, i.e., {T1, T3} and an integral number of each circuit;
K_{pt}: the cost of leasing circuit type $t \in T_p$ to link $p \in P$ ($/month);
S: the set of all O-D pairs;
W_s: average traffic arrival rate on O-D pair $s \in S$ (packets/sec);
M_{pt}: the number of DS-0 channels in circuit type $t \in T_p$ for physical link $p \in P$;
C: the set of all possible c-sequences.

The cost of leasing a particular circuit of type $t \in T_p$, K_{pt}, depends on distance. For example, according to AT&T Tariff No. 9 [11], the lease rate for one T1 circuit consists of a fixed charge of $2,600 and about $15 per mile per month. For T3 circuits, there is a fixed charge of $6,000 per month and a mileage charge based on airline miles between cities. The mileage charge for a T3 varies from $180 per month for a one-year contract to $130 per month for five years. The economies of scale are evident in the tariff structure for digital circuits, as shown in Fig. 3. For example, the cost of a T3 circuit is comparable with the cost of as few as four T1 circuits for a distance of less than 50 miles, i.e., much cheaper than 28 T1s, the equivalent of one T3 in capacity. The set T_p also depends on the length of physical link p. If the length of the physical link p is 500 miles, the economic set is defined as {1 T1, 2 T1s, 3 T1s, 4 T1s, 5 T1, 6 T1, 7 T1, 8 T1s, 9 T1s, 1 T3}, since the cost of 10 T1s is higher than 1 T3, while 1 T3 has much more capacity. If the distance is 100 miles, the economic set is defined as {1 T1, 2 T1s, 3 T1s, 4 T1s, 5 T1, 1 T3}. Other examples of this notation can be found in the section on numerical results.

To summarize, our decision variables are:

- *physical link and capacity selection*:
  y_{pt}, which is defined as 1 if circuit type $t \in T_p$ is leased to link $p \in P$ and 0 otherwise (e.g., $y_{AB} = 1$ if the link AB is chosen for the physical network);
- *logical network configuration and channel assignment:*
  n_c, the number of DS-0 channels assigned along c-sequence $c \in C$ (e.g., $n_{ABC} = 50$ if 50 DS-0

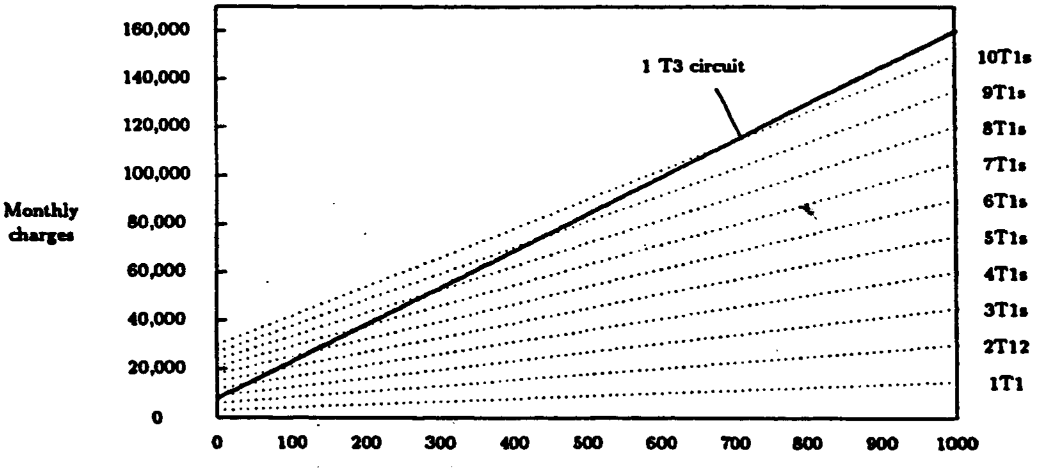


Fig. 3. Break-even point between T1 and T3 circuits.

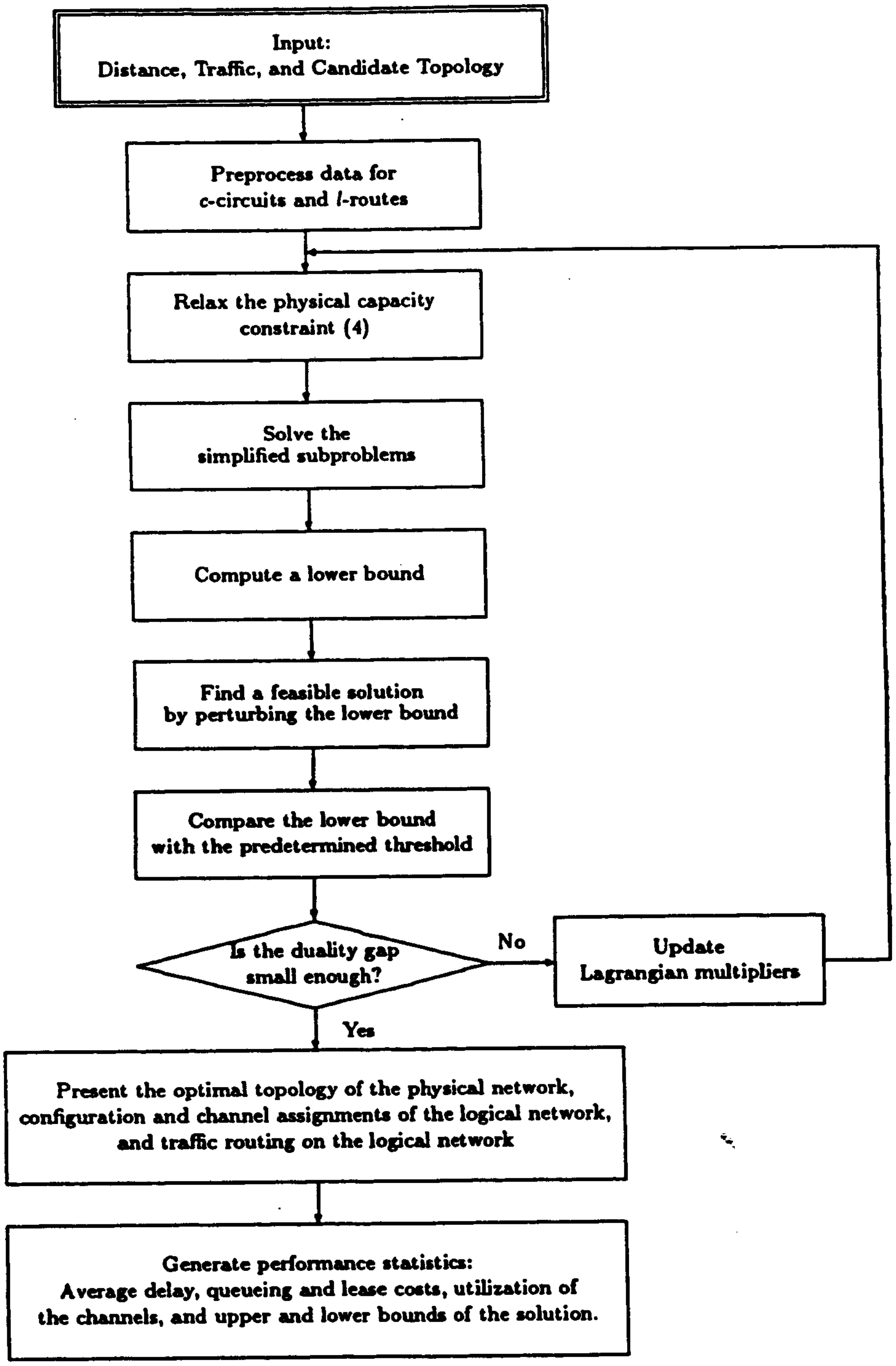


Fig. 4. Flow chart of the solution procedure.

Table 2
The monthly cost of leasing a type t line if used for link p, K_{pt} in \$/month

$p\backslash t$	1	2	3	4	5	6	7	8	9	10	11	12
(1,2)	14735	29470	44205	58940	73675	88410	103145	117880	132615	147350	151620 *	-
(1,5)	26750	53500	80250	107000	133750	160500	187250	214000	240750	267500	294250	295800 *
(2,3)	35195	70390	105585	140780	175975	211170	246365	281560	316755	351950	387145	397140 *
(2,5)	18950	37930	56895	75860	94825	113790	132755	151720	170685	189650	202380 *	
(3,4)	8405	168150	25215	33620	42025	50430	58835	67240	75645	75660 *	-	-
(4,5)	25715	51430	77145	102860	128575	154290	180005	205720	231435	257150	282865	283380 *

* Cost of leasing one T3 circuit for link p

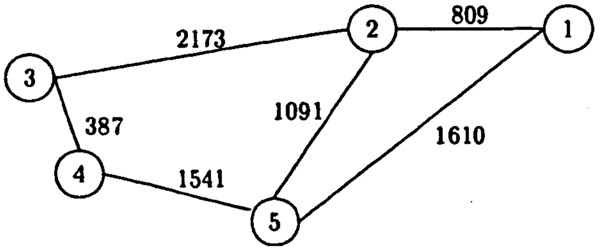


Fig. 5. The five-node network structure. The numbers indicate the distance in miles.

3.1. Five-node test cases

The locations for the five cities selected and the candidate physical links are shown in Fig. 5. The length of each of the candidate physical links, as measured in airline mileage, is also shown. (The five cities in Fig. 5 represent New York, Chicago, San Francisco, Los Angeles, and Houston.)

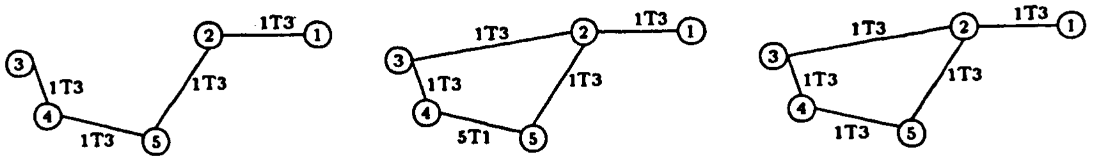
The parameters K_{pt}, the lease cost of using link type t per month for the physical link p, are calculated in Table 2, based on the tariff structure presented in Fig. 3. The parameters M_{pt}, the capacity in units of the number of DS-0 channels of line type t for physical link p, are also presented in Table 1. The row and column headings of these tables represent the physical link set and the line types for a given physical link.

Table 2 shows that the cost of a single T3 circuit is comparable to the cost of 10 to 12 T1 circuits, depending on the distance between nodes. For example, consider link $p=(1,2)$, with a length of 809 miles. The monthly rate for leasing 6 T1s is \$88,410 per month. This table also shows that the cost of leasing 11 T1 circuits for physical link (1,2) is higher than the cost of leasing a single T3 circuit. (The cost of leasing 11 T1s for link $(1,2) = (2600 + 15 \times 809) \times 11 = \$162{,}085$, and the cost of leasing $1\ \mathrm{T3} = 6000 + 180 \times 809 = \$151{,}620$. Hence, the lease of 1 T3 is cheaper than that of 11 T1s.) Yet a single T3 provides significantly more capacity, so the network design algorithm is expected to exploit the economies of scale by using a T3 circuit that brings extra capacity for other crossconnections with no additional cost. Table 2 shows that the economic break-even points for using a T3 for physical links (1,2), (1,5), (2,3), (2,5), (3,4), and (4,5) are 11, 12, 12, 11, 10, and 12 T1 circuits, respectively.

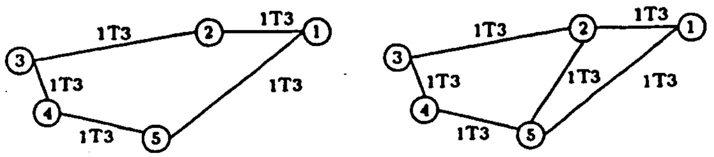
Given the five-node setting, different test cases were created by varying either the level of traffic volumes between cities or the delay cost parameter (D). We started with D = 1500 and varied the volume of traffic as shown in Table 3, which shows the arbitrary O-D pair traffic data for three different cases. For example, the traffic requirement for O-D pair (2,5) for case 2 is 3500

Table 3
Traffic requirement for each O-D pair (packets/sec)

O-D	(1,2)	(1,3)	(1,4)	(1,5)	(2,3)	(2,4)	(2,5)	(3,4)	(3,5)	(4,5)
case 1	3000	4000	3500	3000	4000	5000	3500	4000	4500	3500
case 2	300	400	350	300	400	5000	3500	4000	4500	3500
case 3	600	800	700	600	800	1000	700	800	900	700



(a) D=1000 (b) D=1500 (c) D=2000 or 2500



(d) D=3000 or 3500 (e) D=4000

Fig. 7. Physical network designs with various delay costs.

a longer path can reduce total lease costs by exploiting the economies of scale through using the larger capacity of a T3. The packet routing on the logical network is always determined by selecting the single-link l-route path from the logical network, as proved by [6,7].

To analyze the effect of different delay cost values on network design, we varied the value of D from 1000 to 4000 with an increment of 500. The traffic pattern follows that of case 1 above. Fig. 7 shows the network designs for the seven values of D. Obviously, as the users' delay cost increases, more candidate physical links are selected and more T3 circuits are used. When D = 4000, the delay cost dominates the lease cost, and therefore all candidate physical links are selected and assigned T3 circuits in order to keep the delay cost as low as possible. On the other hand, when D = 1000, the lease cost is the dominant cost component, and the best solution is one that achieves high circuit utilization.

Table 5 summarizes the performance of our solution procedure as well as some results found in the best solutions. It shows the lower and upper bounds for the optimal solutions, the relative gap between the two bounds [defined as (upper bound − lower bound)/upper bound], the average delay per packet in seconds, and the

Table 5
Numerical results for five-node example

D [a]	Upper bound	Lower bound	Gap [b]	Queuing Cost	Lease cost	Avg delay/packet [c]	Avg util [d]
1000	1918319	1731218	0.097	1205279	713040	0.032	0.46
1500	2464305	2209467	0.103	1508930	955375	0.026	0.37
2000	2894552	2660409	0.081	1784372	1110180	0.023	0.33
2500	3340745	3095150	0.073	2230468	1110180	0.023	0.33
3000	3735013	3519218	0.058	2531413	1203600	0.022	0.29
3500	4102190	3937017	0.040	2898590	1203600	0.022	0.27
4000	4635052	4350129	0.061	3229073	1405980	0.021	0.26

[a] Unit delay cost per second.
[b] The gap is defined as (upper bound-lower bound)/upper bound.
[c] In seconds.
[d] Utilization of logical links.

Table 6
Numerical results for ten-node example

D [a]	Upper bound	Lower bound	Gap [b]	Queuing cost	Lease cost	Avg delay/packet [c]	Avg util. [d]
1000	4548401	4017102	0.117	2260541	2287860	0.025	0.37
1500	5771206	5147337	0.108	3372191	2399015	0.025	0.37
2000	6927873	6212636	0.103	4501518	2426355	0.025	0.37
2500	7928486	7235505	0.087	5421201	2507285	0.024	0.33
3000	9057723	8229726	0.091	5940458	3117265	0.022	0.29
3500	10084978	9202517	0.087	6727733	3357245	0.021	0.26
4000	10945168	101557929	0.072	7645483	3299685	0.021	0.26

[a] Unit delay cost per second.
[b] The gap is defined as (upper bound-lower bound)/upper bound.
[c] In seconds.
[d] Utilization of logical links.

average utilization of the logical links. The cost term is separated into two parts: queuing cost and lease cost.

3.2. Ten-node test cases

A second group of test cases were created using ten cities across the United States as nodes for the private data network. (The cities selected are Seattle, San Francisco, Los Angeles, Kansas City, Houston, Chicago, Atlanta, Boston, New York, and Miami.) Fig. 8 shows the locations of these cities and twenty-one candidate physical links connecting them. The length of each of the candidate physical links, as measured in airline mileage, is also shown. The average traffic load between all O-D pairs is 2000 packets/s.

As in the five-node example, different test cases were created by varying the delay cost parameter. The topologies generated for the cases D = 1000, 2000, 3000, and 4000 are shown in Fig. 9. As expected, as the value of D increases, more candidate physical links are selected, and each link is more likely to use a T3. The topologies chosen for smaller delay cost parameters are sparser. For example, Fig. 9(a) shows that twelve links with single T3 circuits are selected from the twenty-one candidate links. For the D = 2000 case shown in Fig. 9(b), three additional T1s are selected for the links (3,5), (5,10), and (8,10). More links are selected when D = 3000 and most when D = 4000; these networks employ both T1s and T3s.

The numerical results for the various scenarios are summarized in Table 6. For the five-node example, the best solutions found were within 4.0% – 10.3% of the optimal solutions; on the other hand, the accuracy of the ten-node example ranges between 8.7% and 11.7%. These relative gaps are somewhat common in this type of large-scale and non-linear mixed integer problem [10,12]. The average utilization in both cases is around 35%, which is close to the desired utilization level in practice. As expected, the average delay is greater when delay costs are lower. These results show that the resulting physical topology is sensitive to the users' delay costs (or to the desired average delay per packet).

The numerical results for both five and ten-node examples were tested on an IBM PC 486 machine. The five-node example included 270 variables with 36 constraints and the results were obtained within 2 minutes. The ten-node network example included about 1000 variables and 200 constraints and the results were obtained within 60–100 minutes.

4. Summary and conclusions

Today's private networks are based on digital technology and typically use T1 and T3 circuits to exploit the economies of scale built into the tariff structure for these digital circuits. T1 and T3 circuits form a reconfigurable network through DCSs, and data networks are defined as logical

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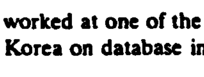

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