On Throughput Optimization in Optical Networks With Regular and Arbitrary Topologies

Jadranka Skorin–Kapov[1] and Jean–François Labourdette[2]

[1] W.A. Harriman School for Management and Policy, State University of New York at Stony Brook
[2] AT&T Laboratories, Holmdel

We present some recent results regarding throughput optimization in logically rearrangeable multihop lightwave networks. Two cases are distinguished: networks having *arbitrary* as well as *regular* connectivity topology. We use the term "arbitrary topology" in contrast to "regular topology", even though the degree of all nodes is fixed and the same in both cases. In both cases we present formulation of the combined station assignment/flow routing problem with the congestion minimization objective. We then outline a heuristic solution strategy based on tabu search. In terms of small congestion (as obtained heuristically), the results suggest that with increased problem sizes, regular topologies become more attractive. In such cases the benefit of having less restricted arbitrary network topology might not be fully utilized. Moreover, such design will implicitly offer benefits associated with management and rearrangement of regular topologies. We further experimented with a combined approach whereby initial assignments to network stations are restricted to a Perfect Shuffle connectivity pattern and obtained by solving a quadratic assignment problem. (In an earlier study, Perfect Shuffle proved to be the most promising among different regular topologies.) Following a transformation of variables, arbitrary connectivity patterns were allowed, and further improvements were performed. Computational results confirm the possible merit of this approach.

Keywords: heuristic solvability, multihop, rearrangeable optical networks, arbitrary and regular network topologies, tabu search

1. Introduction

Optical networks offer great flexibility in allowing reconfiguration according to changing traffic patterns. In this paper we discuss congestion minimization or, equivalently, *throughput optimization* in such networks. Assumptions on the network include: the flow between any two nodes can be routed via intermediate nodes (i.e. multihop network); the flow from a source can be split and reach a sink via different routes; traffic flows are permitted to be asymmetric. Relevant research on rearrangeable optical networks falls in two categories, dealing with networks having either arbitrary or regular connectivity topology [Labourdette, 1997; Mukherjee, 1992]. We use the term "arbitrary topology" in contrast to fixed "regular topology", even though the degree of all nodes is fixed and the same in both cases.

Problems with regular as well as with arbitrary connectivity topologies have been shown to be NP-complete.

In an earlier work, [Skorin-Kapov and Labourdette, 1995] addressed the congestion minimization problem on an arbitrary network topology. (Apart from the prescribed number of receivers and transmitters per node, there is no restriction on the design of logical connectivity graph). There is an available spectrum of wavelengths accessible to and shared among all stations using Wavelength Division Multiplexing (WDM). Tuning a transmitter of node i and a receiver of node j to the same wavelength creates a logical link (i, j) through which traffic can be sent. Retuning transceivers results in a new connectivity diagram, making logical connectivity independent of the physical architecture. An example

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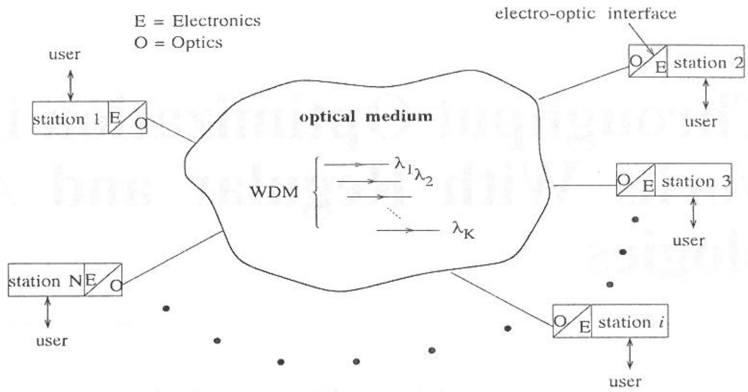

Fig. 1. Network architecture

of a rearrangeable multihop lightwave network is displayed in Figure 1.

Figure 2 displays three commonly proposed broadcast physical topologies for the optical medium: the bus topology, the tree topology, and the star topology.

In a typical architecture, each network station is equipped with a small number $(p+1)$ of transmitters and receivers that tap into the fiber transmission medium, and a small $(p+1) \times (p+1)$

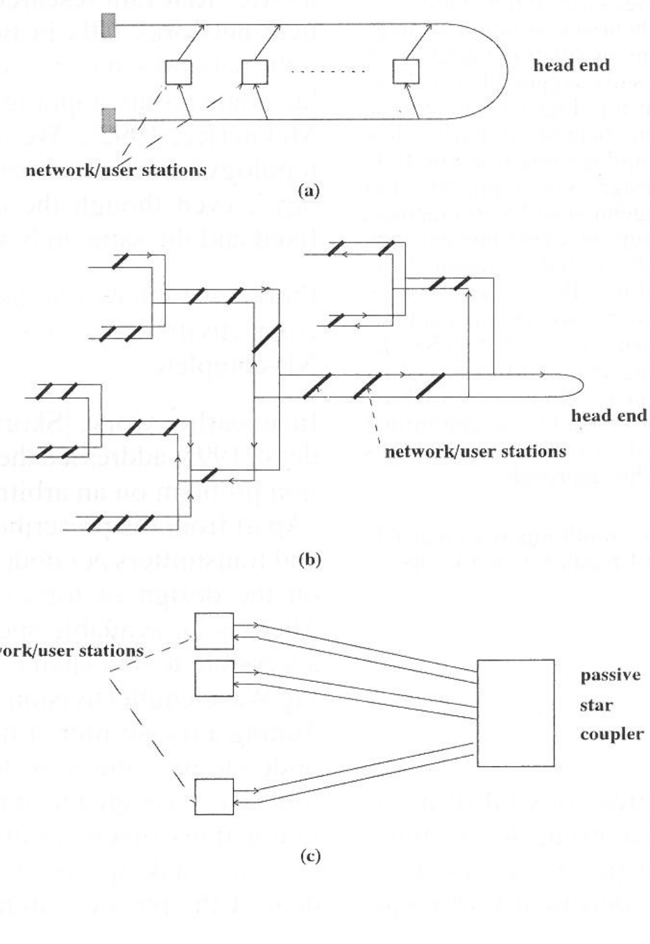

Fig. 2. Examples of passive broadcast physical topologies: (a) linear bus, (b) tree, and (c) star

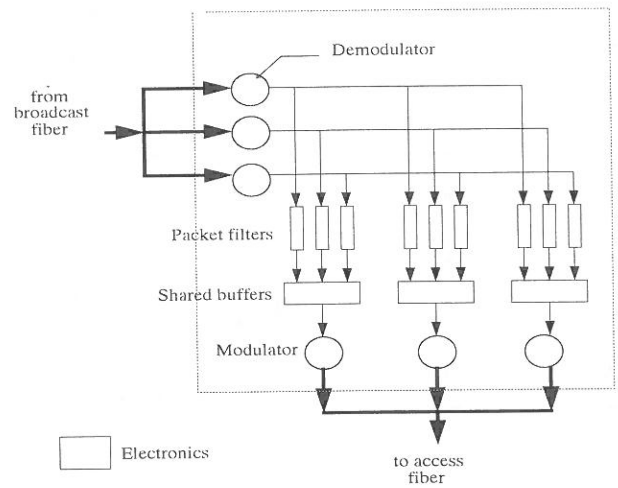

Fig. 3. 3-by-3 network station (p=2)

electronic switch which assigns packets from station receivers to station transmitters. Each network consists of the so-called access part (to communicate with the user stations) as well as the transport part (to communicate with other network stations). One of these transceivers is assigned to the access portion of the network, and the remaining p are assigned to the transport portion of the network. A schematic diagram of a network station with a crossbar switching fabric and output queuing is shown in Figure 3.

For a given traffic matrix (i.e. the matrix of flows between nodes), our objective is to minimize the maximal flow on any link by finding the best logical connectivity diagram (the so-called connectivity problem) and optimizing the corresponding flow assignment to its links (the routing problem). A number of other possible objectives is presented in a recent survey [Labourdette, 1997].

The combined flow and wavelength assignment problem is a very difficult combinatorial problem, hence, it is partitioned into two subproblems and solved heuristically. For networks with arbitrary connectivity topology, the connectivity subproblem is a linear assignment problem maximizing the one-hop path traffic, and the corresponding routing subproblem is a multicomodity flow problem.

A drawback of the approach dealing with arbitrary connectivity topologies could be the large variability between node pairs with respect to performance and connectivity in case of failure. Consequently, a number of regular network topologies (Shuffle-based, de Bruijn graphs, Manhattan Street Network) have been proposed that exhibit good properties with respect to reliability and number of paths between any two nodes [Mukherjee, 1992]. Usually, those are connected graphs having nice properties (small degree and diameter) implying that nodes can be connected with a small number of receivers and that the flow can be transferred in a small number of hops. Some examples of regular connectivity graphs are given in Figure 4 and 5.

Relevant work on Perfect Shuffle regular topology includes [Banerjee and Mukherjee, 1993], where the objective was to minimize a weighted average hop distance. In [Banerjee, Mukherjee and Sarkar, 1994] heuristic algorithms are developed and applied to linearly constrained (bus) optical networks with the additional assumption that the traffic flows are symmetric.

In a recent work [Skorin-Kapov and Labourdette, 1997] present the problem of minimizing congestion on a network with *any* regular connectivity graph. A strategy to solve it heuristically is adopted from their tabu search strategy, developed for arbitrary network topologies. The problem of congestion minimization over regular topologies is also decomposed into two subproblems: a quadratic assignment and a multicommodity network flow routing problem. The quadratic assignment subproblem seeks a 0/1 solution (assignment of stations to nodes) which

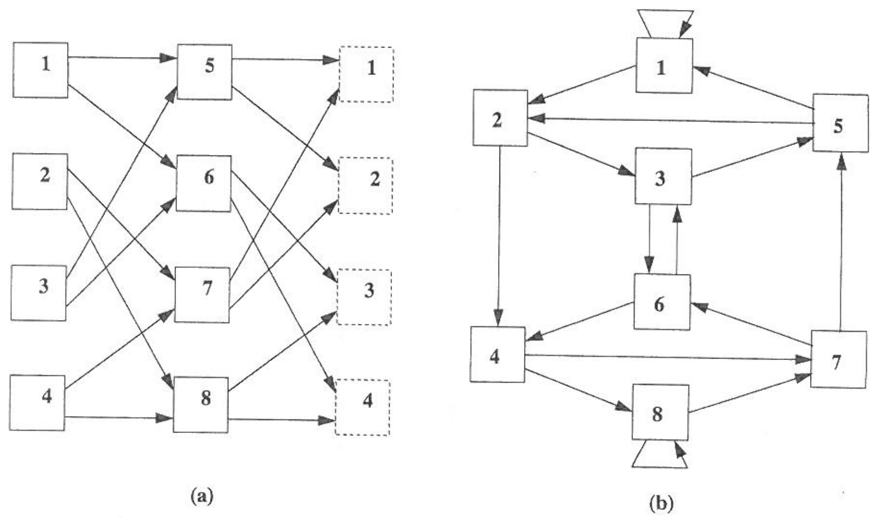

Fig. 4. Examples of logical regular connection diagrams: (a) $(N,p) = (8,2)$ recirculating perfect Shuffle graph, and (b) $(N,p) = (8,2)$ de Bruijn graph

maximizes the one hop path traffic, and the routing subproblem calculates amounts of flow on usable links and tries to minimize congestion.

In both cases (i.e. networks with arbitrary as well as regular connectivity topologies), heuristic algorithms based on tabu search include strategies to guide the search out of a local optimum, and to diversify it. In previous work computational experiments were performed to test algorithms and to compare the use of arbitrary versus regular topology for different sizes of networks. The task was to provide some insight to the importance of having the design freedom, which is implicit in the use of arbitrary topology. In this paper we perform computational experiments with the combined strategy as follows: use regular connectivity topology (Perfect Shuffle) for getting initial solutions via quadratic assignment subroutine, then allow for the less restricted arbitrary topology for local improvements. The results suggest possible merit of such an approach.

This paper is organized as follows. Mixed integer formulations of the problems are given in Section 2. In Section 3, tabu search strategy is outlined. Results are discussed in Section 4. Section 5 concludes the paper and indicates some directions for future research.

2. Formulations of the problem

2.1. Arbitrary topologies

The flow and wavelength assignment problem over *arbitrary* topologies (*FWA*) was previously considered in e.g. [Labourdette and Acampora, 1991; Skorin-Kapov and Labourdette, 1995]. It

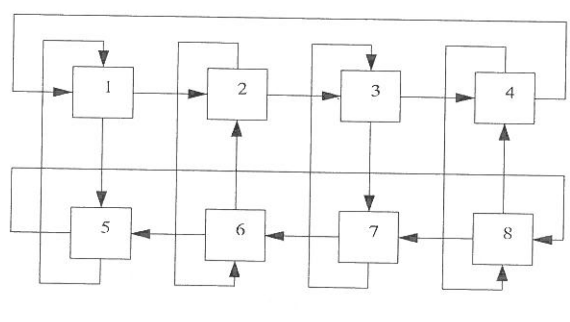

Fig. 5. Manhattan Street Network for $(N,p) = (8,2)$

can be formulated as a mixed integer problem as follows. The input data is given via an $N \times N$ matrix T, where T_{st} denotes the traffic flow from source s to sink t. The number of transmitters and receivers is set to p for any node, and the capacity of any link equals C. Let z_{ij} be a $\{0,1\}$ variable indicating whether or not the link (i,j) is used in the network, and let f_{kij} be a continuous variable indicating the amount of flow originating at source k, sent through the link (i,j). The formulation is then:

$$\min \ F$$

s.t.

$$\sum_k f_{kij} \ \leq \ F \quad \text{for all } i,j,\ i{\neq}j \qquad (1)$$

$$\sum_k f_{kij} \ \leq \ Cz_{ij} \quad \text{for all } i,j,\ i{\neq}j \qquad (2)$$

$$\sum_{i\neq j} f_{kij} - \sum_{i\neq j} f_{kji} \ = \ T_{kj} \quad \text{for all } k,j,\ k{\neq}j \qquad (3)$$

$$\sum_{j\neq i} z_{ij} \ = \ p, \quad \text{for all } i \qquad (4)$$

$$\sum_{j\neq i} z_{ji} \ = \ p, \quad \text{for all } i \qquad (5)$$

$$0 \leq f_{kij},\ z_{ij} \in \{0,1\}, \text{ for all } k,\ i,\ j,\ i \neq j$$

Equation (1) assures that the maximum flow on any link is minimized, (2) enforces the capacity constraints on links, (3) are conservation of flow constraints, and (4, 5) are assignment type constraints assuring p transmitters and receivers on any node.

An initial solution to this problem can be obtained by decomposing it into two subproblems: the connectivity and the routing problems (see [Labourdette and Acampora, 1991; Skorin-Kapov and Labourdette, 1995]). The connectivity problem (CP) is a *linear assignment problem* whose goal is to determine a $0/1$ solution which maximizes the one hop path traffic, formulated as follows:

$$\max \sum_{ij} T_{ij} z_{ij}$$

s.t.

$$\sum_{j\neq i} z_{ij} \ = \ p, \quad \text{for all } i \qquad (6)$$

$$\sum_{j\neq i} z_{ji} \ = \ p, \quad \text{for all } i \qquad (7)$$

$$0 \leq z_{ij} \leq 1 \ \text{ for all } i,\ j,\ i \neq j$$

After solving the connectivity problem, its solution (say $\bar{z_{ij}}$) is used in the formulation of the routing problem (RP), which is an instance of a *multi-commodity flow problem*:

$$\min \ F$$

s.t.

$$\sum_k f_{kij} \ \leq \ \bar{z_{ij}}F \quad \text{for all } i,j,\ i{\neq}j \qquad (8)$$

$$\sum_{i\neq j} f_{kij} - \sum_{i\neq j} f_{kji} \ = \ T_{kj} \quad \text{for all } k,j,\ k{\neq}j \qquad (9)$$

$$0 \leq f_{kij}, \ \text{ for all } k,\ i,\ j,\ i \neq j$$

2.2. Regular topologies

Following a presentation of the (FWA) problem on networks with arbitrary connectivity pattern, we now present the formulation of the problem of minimizing congestion on a network with *any regular* connectivity graph, with the same input flow data given via matrix T. The existing regular connectivity among network stations can be represented by the connectivity values $\beta_{ij} \in \{0,1,\ldots,p\}$:

$$\beta_{ij} \ = \ \text{number of connections from location } i \text{ to location } j \qquad (10)$$

Without loss of generality, we assume $\beta_{ij} \in \{0,1\}$, i.e. there is at most one connection from any node to any other node (which is the case in all well-known regular graphs).

To formally model the set of regular connection diagrams, a set of assignment variables $z_{ik} \in \{0,1\}$ is introduced as follows:

$$z_{ik} = \begin{cases} 1, & \text{if network station } k \text{ is assigned to location } i; \\ 0, & \text{otherwise.} \end{cases} \quad (11)$$

Let f_{kij} be a continuous variable indicating the amount of flow originating at source (station) k, sent through the link between locations i and j.

The flow and wavelength assignment problem over regular topologies ($RFWA$) is then formulated as:

$$\min \ F$$

$$\text{s.t.}$$

$$\sum_k f_{kij} \leq \beta_{ij} F \quad \forall\, i,j, i{\neq}j \quad (12)$$

$$\sum_{i \neq j} f_{kij} - \sum_{i \neq j} f_{kji} = \sum_{l \neq k} T_{kl}(z_{jl} - z_{jk}) \ \forall\, k,j \quad (13)$$

$$\sum_k z_{ik} = 1 \quad \forall\, i \quad (14)$$

$$\sum_i z_{ik} = 1 \quad \forall\, k \quad (15)$$

$$f_{kij} \geq 0, z_{ik} \in \{0,1\} \ \forall\, k,i,j$$

Similarly as in the case of networks with arbitrary connectivity topology, this problem is decomposed and solved heuristically. Due to its structure, the decomposition results with quadratic assignment and routing subproblems. The quadratic assignment (QA) subproblem provides an *initial* assignment of network stations to locations by maximizing the one hop path traffic. (Stations having bigger flow between themselves are placed to neighboring locations.) It is formulated as follows:

$$\max \ \sum_{k,l} \sum_{i,j} T_{kl} \beta_{ij} z_{ik} z_{jl}$$

$$\text{s.t.}$$

$$\sum_k z_{ik} = 1 \quad \forall\, i \quad (16)$$

$$\sum_i z_{ik} = 1 \quad \forall\, k \quad (17)$$

$$z_{ik} \in \{0,1\} \ \forall\, k,i$$

This problem is NP-hard and, hence, solvable heuristically. A number of heuristic algorithms for solving the quadratic assignment problem exist, including tabu search based algorithms (e.g. [Chakrapani and Skorin-Kapov, 1992, 1993; Skorin-Kapov, 1990, 1994]). The obtained assignment matrix is given as input to the routing subproblem. The flow is routed along the lines of a regular connectivity graph, so that the maximal flow on any link is minimized. The routing problem (RP) is a multicommodity network flow problem:

$$\min \ F$$

$$\text{s.t.}$$

$$\sum_k f_{kij} \leq \beta_{ij} F \quad \forall\, i,j \quad (18)$$

$$\sum_{i \neq j} f_{kij} - \sum_{i \neq j} f_{kji} = \sum_{l \neq k} T_{kl}(\bar{z_{jl}} - \bar{z_{jk}}) \ \forall\, k,j \quad (19)$$

$$f_{kij} \geq 0 \ \forall\, k,i,j$$

where $\bar{z_{jl}}$, $\bar{z_{jk}}$ are known.

2.3. Transformation for the combined approach

An interesting approach to deal with arbitrary topology is to use one of the regular topologies (e.g. Perfect Shuffle) to obtain an initial solution, and then transform that solution to an arbitrary network solution. Namely, combinatorial variables in the regular connectivity case are assignment variables $z_{ik} = 1$ if network station k is assigned to node i of the regular connectivity graph, and 0 otherwise). In the arbitrary connectivity case, $y_{kl} = 1$ if there is a link (obtained by retuning a transmitter/receiver pair) between network stations k and l. Given β_{ij}, the set of connectivity values for a regular graph, and the corresponding solution with z-variables, y-variables can be obtained as

$$y_{kl} = \sum_{ij} \beta_{ij} z_{ik} z_{jl}. \quad (20)$$

We use this transformation to test a heuristic approach for congestion minimization of networks with arbitrary connectivity patterns, by combining it with promising regular connectivity strategy.

3. Tabu search strategy

After obtaining an initial solution for the congestion minimization problem, further improvements are attempted in a greedy way by relocating network stations (pairwise exchange), and by resolving the routing subproblems. Motivated by the success of the tabu search approach to the flow and wavelength assignment (*FWA*) problem with arbitrary connectivity pattern (see [Skorin-Kapov and Labourdette, 1995]), the authors further developed a tabu search strategy for dealing with congestion minimization on optical networks with regular connectivity topologies [Skorin-Kapov and Labourdette, 1997]. Tabu search (see e.g. [Glover, 1989,1990]) presents a rich and general framework for utilizing information from past search in order to escape from local optimality, to intensify the search in promising areas, and to diversify the search by visiting new areas of feasible space.

In the sequel we briefly describe the tabu search strategy developed for congestion minimization in multihop optical networks. The strategy is a combination of strategies for regular and arbitrary networks [Skorin-Kapov and Labourdette, 1995, 1997].

Initially, as in the context of the (*RFWA*) problem, the solution can be characterized as (*assig, rout, F*). *Assig* is the assignment matrix with $assig(i, l) = 1$ if station l is assigned to location i; *rout* is the matrix of flow values on available links; and F is the maximal flow value.

Tabu search is first introduced in heuristic solvability of the QA subproblem, known as one of the most difficult combinatorial problems. Having an initial assignment of network stations and allocation of flow, the main tabu search strategy controls pairwise exchanges of stations in order to improve the solution. After applying the transformations of variables given in (20), we continue with improvements based on arbitrary connectivity pattern, i.e using the formulation for the (*FWA*) problem. In this case, the solution is denoted as (*con, rout, F*), where *con* denotes a connectivity matrix, *rout* is the corresponding matrix of flow values (obtained by optimally solving the multicommodity flow problem on *con*), and F is the maximal flow value. For a given solution, we define its neighbor (con^n, $rout^n$, F^n) as the feasible solution obtained by performing a branch-exchange (BE) operation, and by re-solving the routing problem. Therefore, the complete neighborhood evaluation would imply solving $O(N^2p^2)$ routing problems, each having $O(N^3)$ variables and $O(N^2)$ constraints.

Due to memory and computational time requirements, complete evaluation becomes prohibitive when dealing with even moderate sized problems. This implies the use of strategies to restrict the search to parts of the neighborhood, i.e. to a special subset of candidates. Tabu search proceeds for a prescribed number of iterations, after which it is diversified by starting from a different initial solution. Such a solution is constructed by using information from previous search in order to avoid previously examined parts of the feasible region. In this paper we tested two strategies with respect to generation of restarting solutions: either via quadratic assignment subroutine utilizing a regular connectivity pattern, or via a linear assignment subroutine when arbitrary network topology is assumed.

4. Computational results

The computational experiments regarding a tabu search approach to throughput optimization of optical networks were performed on a Sun SPARC 2 machine. The algorithms were coded in C, and the routing subproblems were solved using Cplex 3.0 callable library from Cplex Optimization, Inc. The data sets used in Skorin-Kapov and Labourdette's studies can be obtained by anonymous ftp from frost.har.sunysb.edu in the directory pub/data.

4.1. Result summary of previous work

The results from [Skorin-Kapov and Labourdette, 1995] regarding networks with arbitrary topologies were overall very good, and compared favorably with the available results from the literature. In all instances, either the best known (or optimal) solution was obtained, or the best known solution was improved.

The next task was to compare networks having arbitrary versus regular topology for different sizes of the problem, and to provide insight to the following questions: Is the freedom implicit in the use of arbitrary topology paid off by significantly better throughput? Is this offset by increased network sizes leading to limited heuristic search? Are the results dependent on different patterns of input data? The results from [Skorin-Kapov and Labourdette, 1997]) concerning comparison of different regular topologies with the arbitrary topology revealed the following. For all 8-dimensional instances except *ring*, the Perfect Shuffle (PS), Manhattan Street Network (MSN), and GEMNET topologies performed similarly with minimal congestion about 19% above the smallest minimal congestions obtained when using arbitrary network topologies. As problem sizes increased, the usage of networks with regular topologies became more attractive (see Tables 2 and 3 in [Skorin- Kapov and Labourdette, 1997].) For some instances, by using the Perfect Shuffle topology, the best results from [Skorin-Kapov and Labourdette, 1995] on networks with arbitrary topology were *improved*. It was interesting to observe that in some instances the congestion obtained *initially* for regular topologies (by using the quadratic programming subroutine) was an improvement over the smallest congestion obtained for arbitrary network topologies. This suggested that the formulation of the Regular Flow and Wavelength Assignment (RFWA) problem, its decomposition into assignment and routing subproblems, and the heuristic of maximizing the one-hop path traffic, are effective and lead to initial solutions of high quality.

4.2. Results for combined regular/arbitrary approach

This result motivated our research in combining the two approaches. Namely, we run experiments with the following two strategies: (1) use perfect shuffle regular connectivity to get the initial solution, then do the transformation of variables and continue with arbitrary connectivity; (2) use perfect shuffle regular connectivity for the initial solution as well as long term memory restarts, while improvements are performed on arbitrary networks. We then compared the performance with our former tabu search strategies dealing with arbitrary and regular connectivities. Because perfect shuffle was the most

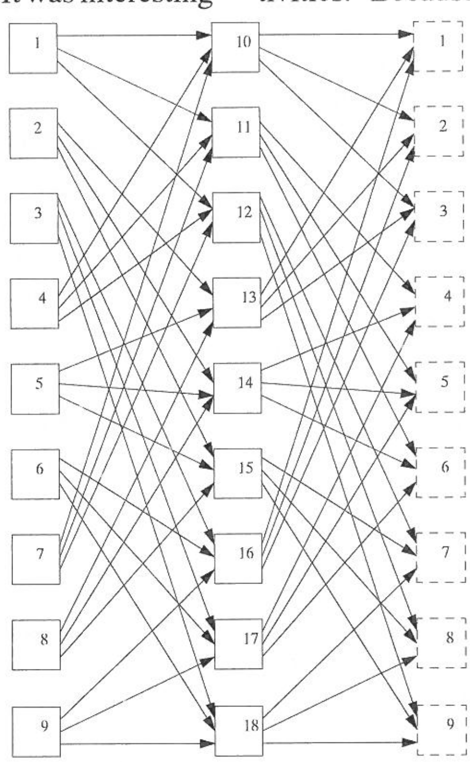

Fig. 6. ShuffleNet for $(N, p) = (18, 3)$

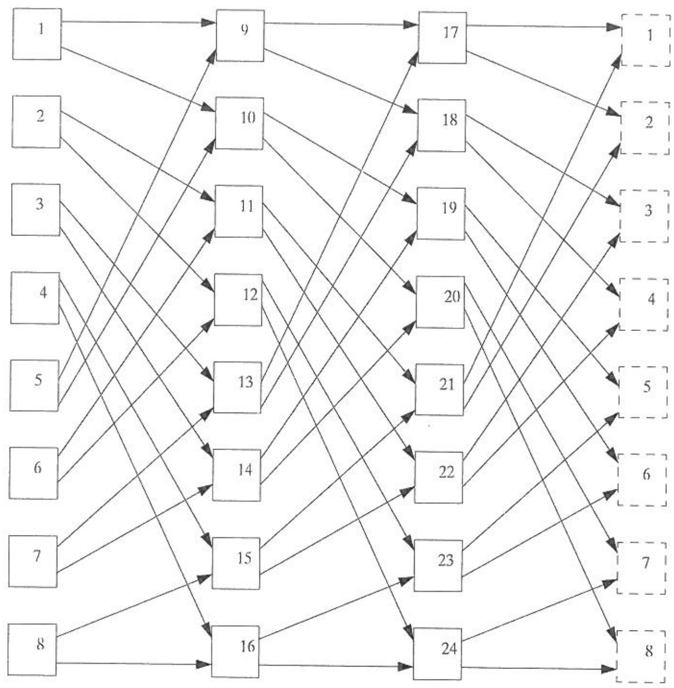

Fig. 7. ShuffleNet for $(N, p) = (24, 2)$

promising regular connectivity network, we restricted our experiments to generate initial solutions via quadratic assignment formulation using perfect shuffle connections. Hence, in selecting problem instances, we were restricted with the sizes of perfect shuffle topology. In order to be able to compare the results, we used 8-, 18-, and 24-dimensional data instances from [Skorin- Kapov and Labourdette, 1997]. Perfect shuffle connections for 18- and 24-dimensional instances are given in Figures 6 and 7, respectively. Recall that the recirculating Perfect Shuffle (PS) is made of $N = kp^k$ nodes arranged in k columns of p^k nodes each. Each of the p^k nodes in a column has p links directed to different nodes in the next column, with the last column connected back to the first column, creating a circulating diagram. The nodal connectivity between adjacent columns is a a generalization of the p-shuffle-exchange connectivity pattern using directed links.

The results of our computational experiments

problem:		**uniform2**	**quasiunif1**	**quasiunif2**	**ring**	**disconn**
Parameters: K=8, tabu_size=2, δ =[1,4], max_iter=30, LTM restart=9, average cpu per iter = 5.98						
arbitrary topology	flow:	6.667	6.100	6.750	12.540	27.540
	iter; LTM:	5;0	2;0	1;0	1;2	1;0
Perfect Shuffle(8,2) start;	flow:	6.667	6.140	6.567	12.660	27.70
arbitrary improv. and LTM restarts	iter; LTM:	7;0	19;2	7;2	12;3	26;5
% above arbitrary:		0.00%	0.66%	-2.71%	0.96%	0.58%
PS(8,2) start and LTM restarts,	flow:	6.667	6.125	6.718	12.600	27.75
arbitrary improvements	iter; LTM:	7;0	18;6	5;8	5;1	27;6
% above arbitrary:		0.00%	0.41%	-0.47%	0.48%	0.76%
Perfect Shuffle(8,2)	flow:	8.000	7.225	7.750	13.950	33.350
	iter; LTM:	initial	15;0	18;1	7;0	27;1
% above arbitrary:		19.99%	18.44%	14.81%	11.24%	21.10%
arbitrary topology (best results from Skorin-Kapov and Labourdette,1995)	flow:	6.667	6.060	6.567	12.400	27.540

Table 1. Tabu search: computational results for different strategies for networks with N=8, p = 2.

problem:		quasiuniform18-1	quasiuniform18-2	quasiuniform18-3
Parameters: K=6, tabu_size=4, δ =[1,4], max_iter=30, LTM restart=3				
arbitrary topology	flow:	241.061	244.406	386.829
	iter;LTM:	8;2	3;0	14;2
	cpu sec:	47359.44	2116.00	88250.11
Perfect Shuffle(18,3) start,	flow:	241.418	240.825	386.292
arbitrary improvements	iter; LTM:	4;2	6;2	6;1
and LTM restarts	cpu sec:	40871.67	47099.75	46342.55
% above arbitrary:		0.15%	-1.46%	-0.14%
Perfect Shuffle(18,3) start	flow:	247.913	255.577	407.403
and LTM restarts,	iter; LTM:	11;2	20;2	30;1
arbirtary improvements	cpu sec:	51727.25	58650.56	77828.79
% above arbitrary:		2.84%	5.40%	5.32%
Perfect Shuffle(18,3)	flow:	252.295	257.615	413.829
	iter; LTM:	2;0	2;0	2;3
	cpu sec:	1090.78	1210.90	88699.80
% above arbitrary:		4.66%	5.40%	6.98%

Table 2. Tabu search: computational results for different strategies for networks with N=18, p = 3.

problem:		quasiuniform24-1	quasiuniform24-2	quasiuniform24-3
Parameters: K=4, tabu_size=4, δ =[1,4], max_iter=10, LTM restart=1				
arbitrary topology	flow:	736.717	777.062	1244.533
	iter; LTM:	9;0	9;1	1;0
	cpu sec:	12837.0	28078.5	2975.0
Perfect Shuffle(24,2) start;	flow:	737.25	732.875	1230.609
arbitrary improvements	iter; LTM:	1;0	0;0	1;0
and LTM restarts	cpu sec:	1236.77	-	3707.15
% above arbitrary:		0.07%	-5.69%	-1.12%
Perfect Shuffle(24,2) start	flow:	729.75	732.875	1230.609
and LTM restarts;	iter; LTM:	8;1	0;0	1;0
arbirtary improvements	cpu sec:	24668.33	-	3707.15
% above arbitrary:		-0.95%	-5.69%	-1.12%
Perfect Shuffle(24,2)	flow:	730.250	732.875	1205.652
	iter; LTM:	7;0	initial	6;0
	cpu sec:	7683.0	-	21274.7
% above arbitrary:		-0.88%	-5.69%	-3.12%

Table 3. Tabu search: computational results for different topologies for networks with N=24, p = 2.

are displayed in Tables 1, 2 and 3. For 8-dimensional problems, the 'regular start' approach resulted with congestion less that 1% above the equivalent 'arbitrary start' in four cases, and 2.71% *below* the 'arbitrary start' in one case (quadiunif2 instance). For 18-dimensional problems, in two out of three cases we achieved better congestion when using regular topology for the initial solution. Using it further for subsequent long term memory restarts did not perform relatively well, although it did better then the strategy of using only the Perfect Shuffle regular connectivity pattern (for improvements as well as restarts). However, using only the Perfect Shuffle regular connectivity strategy for 18-dimensional problems resulted with congestions less that 6% (on average) above the corresponding arbitrary connections, as opposed to regular connectivity congestions which were on average about 18% above the arbitrary connectivity congestions for smaller, 8-dimensional, problem instances. For the 24-dimensional data, involving regular connectivities in heuristic search was beneficial in all cases: using it just for getting an initial solution via (QA) subroutine; using it for getting an initial solution as well as for long term memory restarts; and finally using it exclusively (i.e. for initial solution as well as improvements). Based on this testing sample, it seems that there is a benefit of using regular connectivity pattern in congestion minimization of optical networks, especially in the light of increased problem sizes.

5. Conclusions and directions for further research

In this paper we presented some recent results regarding throughput optimization in lightwave networks. Such networks have the ability to reconfigure the logical connectivity among nodes with respect to changing traffic patterns, thus making the logical connectivity independent of the underlying fiber physical topology. The heuristic solvability of the flow and wavelength assignment problem over arbitrary as well as regular topology has been improved by developing tabu search based algorithms.

Regarding the heuristic minimization of congestion, the results show that arbitrary topologies lead to better performance for smaller instances. With the increased problem sizes, the performance of regular topologies has improved (relative to the use of arbitrary topologies). This might be due to the different formulation of the problem leading to better quality initial solutions. The quality of the initial solution is important, since the computational burden associated with the complexity of the problem implies that the heuristic search can explore only limited parts of the feasible region.

Future work on congestion minimization of optical networks would include: (1) additional tabu search strategies to deal with larger problems, embedded in parallelization approaches and taking advantage of faster procedures for solving routing subproblems; (2) incorporation of propagation and queuing delay costs in the problem which will modify its formulation, but will more accurately represent the possible application; (3) development of strategies to balance between the current objective of minimizing the maximal congestion and the objective of minimizing the impact of the reconfiguration phase on time and traffic (which makes the network vulnerable); (4) exploration of composite topologies, i.e. development of complex network topologies in which different parts correspond to different basic regular topologies (such as Perfect Shuffle, de Bruijn, GEMNET or MSN graphs). With such approach, the number of instances allowing certain regularity in their topological design might be increased. (Due to special structures, regular topologies do not exist for every network size.) The challenge would be to properly connect parts of the network with different regular topologies and a residual having arbitrary topology.

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Contact address:
Jadranka Skorin–Kapov
W.A. Harriman School for Management and Policy
State University of New York at Stony Brook
Stony Brook, NY 11794–3775
email: jskorin@frost.har.sunysb.edu

Jean-François Labourdette
AT&T Laboratories
Holmdel, NJ 07733
email: labourdette@att.com

JEAN-FRANÇOIS P. LABOURDETTE received the Diplome d'Ingenieur from Ecole Nationale Superieure des Telecommunications, Brest, France, in 1986, and the M.Sc. and Ph.D. degrees in electrical engineering from Columbia University, New–York, in 1988 and 1991, respectively.

From 1987 to 1991, he was a Graduate Research Assistant at the NSF Center for Telecommunications Research, Columbia University, working on reconfigurable lightwave networks. He spent the summer of 1990 at Motorola Codex, Mansfield, MA, investigating the design of fast packet networks for integrated traffic. He joined AT&T Laboratories, Holmdel, NJ, in 1991. From 1991 to 1996, he conducted core network planning activities, working on circuit-switched network routing, dynamically recon figurable T1/T3 networ k architectures and ATM networking. He was promoted to Principal Technical Staff Member in 1996. He is currently with the Frame Relay department, working on global Frame Relay service architecture and operations.

His research interests include lightwave network architectures, network performances, traffic optimization and reconfiguration management of circuit-switched and packet networks.

Dr. Labourdette was a recipient of a Lavoisier Scholarship from the French government in 1986–1987, and was a Motorola Scholar in 1989–1990 and 1990–1991. He received the Eliahu I. Jury award for excellence in Systems, Communications or Signal Processing at Columbia University in 1992. He has served as a member of the Techn ical Program Committee for the IEEE INFOCOM conference from 1994 to 1997 and for the IEEE ICC conference in 1994. He is a senior member of the IEEE.

JADRANKA SKORIN–KAPOV received her B.Sc. (1977) and M.Sc. (1983) degrees in Applied Mathematics from the University of Zagreb, and her Ph.D. (1987) in Operations Research from the University of British Columbia, Canada. She is currently an Associate Professor in the W. A. Harriman School for Management and Policy, State University of New York at Stony Brook. Her research interests include combinatorial optimization and development of solution procedures for difficult optimization problems arizing in telecom munications, manufacturing, and facility layout and location. She has published extensively, including articles in Mathematical Programming, Operations Research Letters, ORSA Journal on Computing, Computers and Operations Research, Discrete Applied Mathematics, Telecommunication Systems, Journal of Computing and Information Technology, European Journal of Operational Research, and Annals of Operations Research.