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Arc-flow based ILP Formulation for the new Millennium Network Share-paths Protections against Indiscriminate Network Multicast Failures.

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Abstract
In this work, several software tools were used for solving greetfield network design problems for the survivability of WDM networks against multicast failures, as well as tools for analysing the blocking probabilities in circuit-switching WDM networks without wavelength converters. In the begining, attention was specifically focused on optimising network design considering link costs comprised of duct costs and traffic dependent fibre costs. A two phase tool was developed in which the first phase generated a set of promising paths from which the second phase, a heuristic based on simulated allocation, can select paths to reduce the network deployment cost. Evaluations showed that the promising path generator supplied path sets of good quality for the nominal network design task but that the sets for protected network design were not quite as good as wanted. The heuristic was compared with ILP optimisation tools and with a commercially available network design tool and it turned out to produce good results.

Keywords; *Network, Sharepaths, Arc-flow, Protection, Multicast, Failures*

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I. Introduction

The network problems that have been under considerions are variants of the multifailure commodity flow problems. Here, they are being considered as the optical network design problems in the mathematical formulation through the use of ILP programs. This is because the ILP programs can act as useful benchmarks for optimizing network design matheuristically because they can be passed directly to ILP optimizers. The optimizers used here are GAMS and CPLEX; GAMS is a preprocessor which takes the formulation or data entered, recast them in a shape that the CPLEX machine can handle and performs some simple pre-optimizations, before passing to another CPLEX which is the real optimization tool to produce results.

There are two major ways to express multiflow failure problems in the ILP programs; as in

1. Arc-flow formulation
2. Link – path formulation

The major difference is that in the arc-flow formulation, it is up to the optimizer to design the paths that will supply demands where as in the link-path formulation one must precompute some paths for each demand, the optimizer only selects from the precomputed paths. However, here, the arc-flow forulation is adopted because it is easier, less cost and gives optimal result values unlike the later if only all possible paths are given as inputs.

Arc- flow formulation

In the arc-flow the network, it is considered as a set of N nodes, and at each node some wavelengths are introduced, either from neighbouring nodes or from traffic source located in the node. The exact same amount that entered must leave the node and which is called conservation principle.

The flows are then indxed by the demands they supply and the wavelengths they use. The traffic flows along directed edges which the directed edges from node **n** to node **m** is carried together with the edge from node **m** to node **n** in a link {**n, m**}. This implies that it is not possible to have more than one link between two nodes in the arc-flow. The optimization procedures for the arc-flow formulation is shown below schematically.

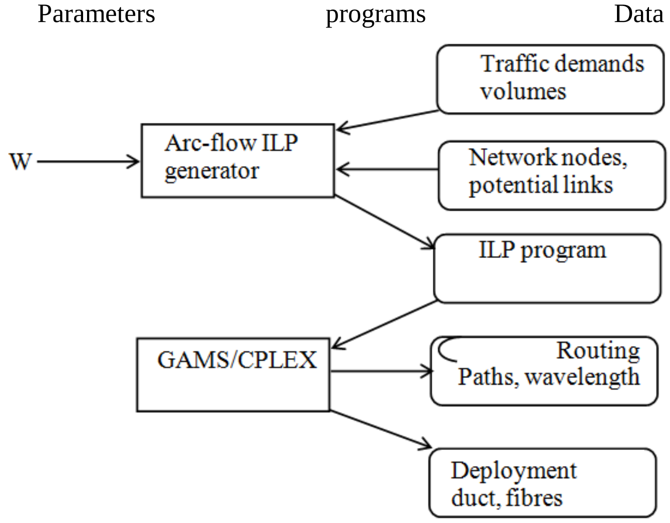


Figure 1: Optimizing WDM network using the arc-flow based ILP.

A simple generator produces the ILP program based on the traffic and network data which passes it to the GAMS/CPLEX optimizer for production of results.
Here in this work, we use the arc-flow formulation method to protect network from failure both the TRP and PDP network protection model (i.e: using it to design network protection in both model). The results were compared.

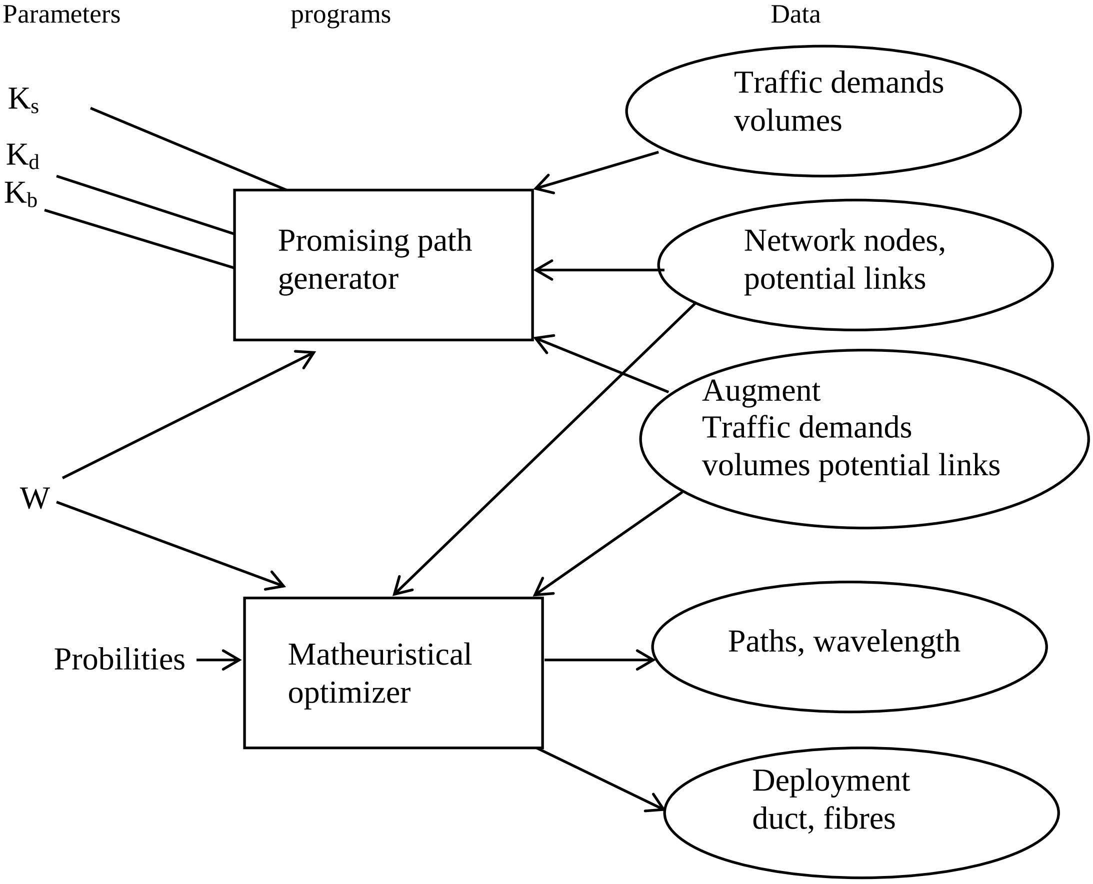


Figure 2; Optimizing WDM network matheuristically (SAN + SAL Approach).

The ILP programs serve as formal approach of the network design problems which can be used directly as input to ILP optimizer, but there are some other variants of the multicommodity flow problem. This work uses heuristical approach which is more viable to present the two instances of matheuristics that perform

optimization by stochastic algorithms: **Simulated annealing** and **simulated allocation**. The overal structure is shown in figure above.
Network are assumed to be in a set of states {0...... S} in which each set of a state, there is a failed edge unless otherwise stated. Each state S corresponds to one edge failure. Though the state formulation is a general approach that allows modelling node failures by letting all edges incident with a node failure in state S be in ∈. But conventionally, S = 0 is considered to be in the normal state where there are no failures, that is, $\in_o = \{ \}$.
In all the network design problems, they share the following indexes, constants, basic variables and objective function; but there are different constants peculiar to each of them.
Indexes:

d ∈ {1.......D}	Traffic demands
S ∈ {0.......S}	Network states
C ∈ {1.......w}	wavelengths
M, n∈ {1.......N}	Network nodes
(nm) ϵ $\varepsilon \leq \{1.......N\}^2$	Directed edges
(nm) ∈ $\varepsilon_s < E$	Directed edges affected in state S
{n, m} ∈ L ≤ p{1.......N}	undirected links

Constants.

$V_d^s \ \epsilon \ N_o$ — *Volume of lightpaths to be realized for demand d in state S*

$n_d^{src} \ \epsilon \ \{1 \ldots \ldots N\}$ — *Indix of the source node for demand d*

$n_d^{dst} \ \epsilon \ \{ 1 \ldots \ldots . N\}$ — *Index of the destination node for demand d*

$C_{\{n,m\}}^{duct} \epsilon \ R_+$ — *Cost of designing the duct on link $\{n, m\}$*

$C_{\{n,m\}}^{fibre} \ \epsilon \ R_+$ — *Cost of deploying a fibre pair on link $\{n, m\}$*

Basic variables:

U{n, m} ϵR_+ Number of required fibre pairs on link {n, m}

α {n, m} ϵ {0, 1} Number of required ducts on link {n, m}

R_1 stands for a set of real numbers that help to speed up the ILP optimizers.

The Total Re-routing Protection Network Design (TRP)
Having introduced the general or conventional procedures of the arc-flow formulation method, it is now being used to enhance optical network designed in TRP model.
The TRP design problem is done by extending the nominal design problem to include the network multifailure states. Ordinarily, if the source or destination node of demand d fails in state S, it cannot in any way supply the demand in which case the network is set as $V_d^s = 0$. There are bound to be some other reasons why a network operator may set $V_d^s \neq V_d^o$.
Despite the general parameters and data of the arc-flow formulation, there are still some additional variables and constriants applicable to any particlar or model used in ensuring protection of the network. Such variables and constraints are as in TRP.
Additional Vatiables:

$X_{d(nm)}^{cs} \ \epsilon \ N_O$ — *flow of demand d on wavelength c along edge (nm) in state S*

$V_d^{cs} \ \epsilon \ R_+$ — *Volume of demand d carried on primary wavelength C in state S*

Constriants:
$\sum_c V_d^{cs} \geq V_d^s$ The total volume of demand d in each state must be supplied by lightpaths of various wavelengths.
σ {n, m} = 0 ⟹ $U_{\{n,m\}} = 0$ Without a duct, there can be no fibres on link (n, m).
There is also the constraints of flow conservation for paths, what goes into node **n** on wavelength C in state S must come out again. There must also be right calculation of required number of fibres in any states S on any wavelength C.

Path Diversity Protection Network Design (PDP).
In the PDP design problem, X_{dm}^{cs} is used to keep track of the flow in every state S, and find the required capacity t_{dnm}^c as the maximum of the X_{dnm}^{cs} over all the states.
Its variables and constraints are the same with that of the TRP except that;

Variables

$t_{dnm}^{c} \ \epsilon \ R_{+}$Required capacity for demand d on wavelength C along edge (nm).

constraints

$X_{dnm}^{cs} \ \leq \ t_{dnm}^{c}$ calculating the required capacity for demand d on wavelength C along edge (n m).

Handling Multiple Link Failures Protection Using SHR

The formulations so far given are capable enough to handle multiple link/path failures, if it is all possibly set. This means that any given set of failed link ε_s, if the network connectivity is strong enough will handle itself to recover failed link/path within a reasonable short time frame, if the ILP programs presented will be able to find a solution. For example, considering the network below, with just one demand from S to d, and three failure states such as; (1) one where two upper links fail, (2) one where two lower links fail, and (3) one where an upper and lower link fail alternatively. So both TRP and PDP are able to fix all situation in each case using the backup paths.

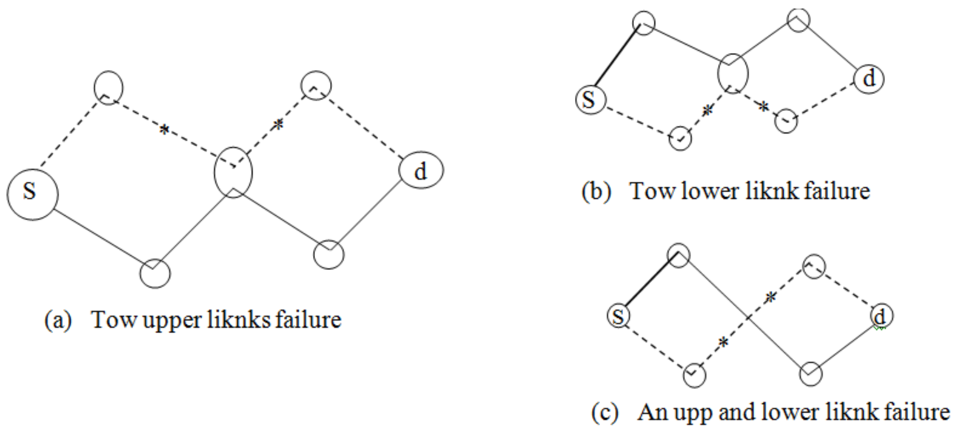


Figure 3: Multiple link failures

This section of the work x- rays the characteristics of self- healing ring. It is diagramatically shown and explained in the figure above.

It is called SONET SHR which is very useful technique for survivability of optical networks. Here networks are designed to have ring architeres. SHR is more useful than other protection technique like APS (antomatic protection switching) because of its flexibility in handling both link and node failures. It uses add/drop multiplexing (ADM) techniques. Unidirectional SHR (USHR) and bi-drectional (SHR) are two types of SHRs. The difference between them is the direction of the traffic flow under normal condition. In USHR, the normal traffic flow goes around the ring in one direction as shown in figure 3(a-b). Any traffic routed to the protection ring because a failure is carried in the opposite direction. But in SHR, working traffic flows in both directions.

However, a bidirectional logical-ring network employs OXC nodes which partitions the network into segments and then interconnects other segments at subchannel level to form logical ring structures. Every segment is independent, which includes a subset of (ADMs) nodes and two pairs of links, one working and the other for protection. The formation of the logical rings from the interconnection of independent segment subchannels preserves the self-healing advantages of conventional bidirectional ring networks and allows greater flexibility to effeciently accommodate bandwidth upgrade request and more robust traffic flow.

II. DATA ANALYSIS

Emperical Evaluation of Promising Path Generation

Having designed the two major programs shown above, the PPG and the matheurishtic optimizer (San + Sal), it is needful to evaluate them (their effectiveness) empirically, in order to prove how good the quality of their results. There are two methods for the evaluation of the results qualities;

1. Benchmarking by comparing with the results of other algorithms which are known to be optimal or to produce good results and
2. The known-result testing by using the programs on problems with a proven optimal values.

Benchmarking

Comparingthe programs, it is pertinent to see a way of benchmarking the PPG algorithm since the ILP solver (GAMS/CPLEX) is capable of giving optimal results if only the problem size is not too large. The results from the two methods are compared to assess their percentage quality. Because the arc-flow formulation is computationally very intensive, it is wise that only few representative of networks and their traffic demands used for the performance evaluations.

Table1: The characteristics of representing networks:

Network	Nodes (N)	Links (L)	Connectivity $2\frac{L-N+I}{(N-1)(N-2)}$	Demands D	Demand volume V
ND	5	10	1	10	37
TRP	7	11	0.33	20	58
PDP	8	21	0.66	27	62

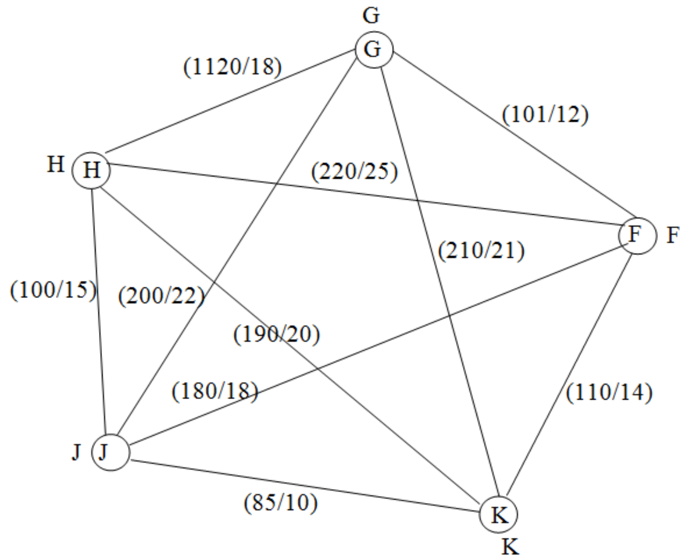


Figure 4: Network 1 and the traffic for quality evaluation of the PPG Algorithm.

Table 2: Decision box of fig. 4.

	F	G	H	J	K
F		1	7	2	5
G	0		4	6	3
H	0	0		3	5
J	0	0	0		1
K	0	0	0	0	

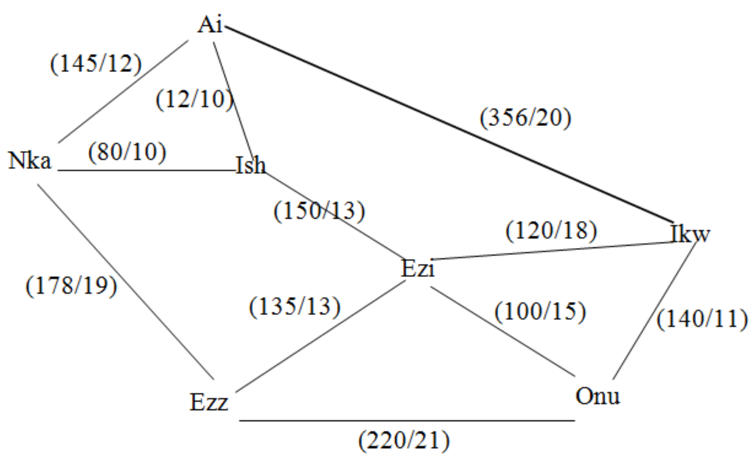


Fig 5.: Network II and the traffic for equality evaluation of the PPG algoritum

Table.3: Decision box of fig.5

	Ai	Nka	Ish	Ezi	Ikw	Onu	Ezz
A1		1	5	2	6	1	2
Nka	0		2	1	1	1	0
Ish	0	0		5	8	3	3
Ezi	0	0	0		6	2	2
Ikw	0	0	0	0		2	4
Onu	0	0	0	0	0		1
Ezz	0	0	0	0	0	0	

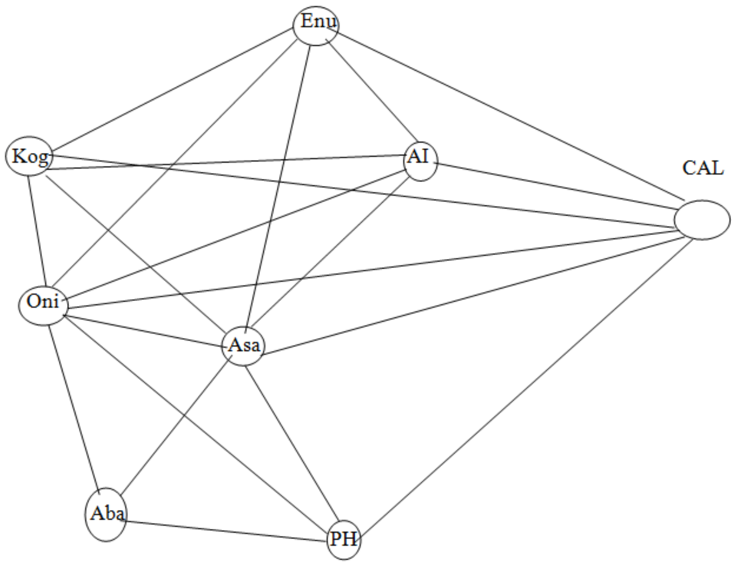


Fig 6: Network III and the traffic for the PPG evaluation.

Table 4: Decision box of fig.6

	Enu	Ai	Kog	Cal	Oni	Asa	Aba	Ph
Enu		1	1	5	4	1	2	3
A1	0		1	2	2	0	1	1
Kos	0	0		3	3	1	1	1
Cal	0	0	0		9	1	3	5
Oni	0	0	0	0		1	3	4
Asa	0	0	0	0	0		1	1
Aba	0	0	0	0	0	0		1
Ph	0	0	0	0	0	0	0	

III. RESULT DISCUSSIONS

Connectivity is a measure of the ratio between links and nodes in a connected network, where the connectivity for a linear network is 0 and for a fully connected network is 1. For each network, the PPG algroritum is run with (Ks, K_d) = (3,2) and (8,3) respectively where $K_b = 0$ in order to obtain a set of promising paths. To ensure a valid backup paths, k_d must be greater than 1, and the values for K_s are chosen as a compromise between a path set containing all the optimal paths and path sets of managable sizes.

Table 5: Comparing PPG results with optimal arc-flow based values

Task	*Net*	*W*	*PPG* $^{k_s=3}_{k_d=2}$ *value*	*%*	*PPG* $^{k_s=8}_{k_d=3}$ *value*	*%*	*Arc-flow value*	*lo bound*	*status*
ND	I		1295	100	1295	100	1295		Optimal
			916	102	894	100	894		Optimal
		1 2 3	726	112	664	102		651	Memout
	II		2283	100	2283	100	2283		Optimal
			1587	103	1559	101		1541	Timeout
		1 2 3	1242	107	1193	103		1158	Timeout
	III		94.28	104	94.07	104	90.58		Optimal
			62.35		62.35				Memout
		1	45.92	101	45.92	101	45.61	44.85	Timeout

		2 3							
TRP	I		2152	105	2088	102	2044		Optimal
			1557		1359				Memout
	1	2 3	1237		951				Memout
	II		4038	112	3659	102	3593		Optimal
			2885		2639				Timeout
	1	2 3	2336	114	2048	100	2046		Timeout
	III		155.09	121	129.88	101	128.56	107.10	Timeout
			106.32	113	81.43	87	93.72	45.24	Timeout
	1	2 3	81.43		71.78				Timeout
PDP	I		2764	101	2742	101	2726		Optimal
			1844	110	1707	102		1676	Timeout
	1	2 3	1390	127	1140	104		1093	Timeout
	II		4946	103	4783	100	4781		Optimal
			3342	104	3228	100	3222	3218	Timeout
	1	2 3	2529	148	2357	138		1712	Timeout
	III		189.11	149	177.39	140		126.84	Timeout
			123.13		117.33				Timeout
	1	2 3	89.29	401	80.75	362		22.28	Timeout

Letting the number of wavelength W per fibre be 1, 2 and 4, the results shown in the table aboveare shown. Figures in the value columns are the solution values which the given optimization method reached, either because it finishes or it exceeds the time limit. For arc-flow, the low bound is the best value the solver has to determine possibly at timeout. While status indicates whether the solver stops because the solution had been proved optimal or because the time/memory limit has been exceeded. For PPG, “%” columnshows the percentage values found using the PPG in relation to the arc-flow value, if it has been found or otherwise the low bound value, if it has as well been found.

The results generally indicate that PPG with $K_s = 8$, $K_d = 3$ produces good results in case where the optimizer reaches feasible solution. Comparing the two PPG columns it would appear that $K_s = 3$, $K_d = 2$ produces few paths toallow finding a globally good result solutions.

Note that when comparing different tasks for the same network-wavelength combinations, for values found before timeout, the ND value is a lower bound for the values of all tasks; the TRP value is a lower bound for the values of all protection tasks and the PDP value is a little bit greater than ND + TRP values which can readily be understood when considering the underlying ILP programs.

Known- Result Testing Evaluations

Using Benchmarking for optimal ILP programs enables comparism with the optimal solution but it has the disadvantage of limiting the problem size to unrealistically small networks. But the limt can be exceeded by producing examples from where the optimal solutions can easily be seen or computed. So if all the fibre costs are set to 0, the optimal result depends neither on the traffic volumes nor the wavelengths per fibre. With this it was found that the ND task is reduced to classic miniumum. The TRP and PDP are subjected to the travelling salesperson (TSP) which is the current state-of-the art of matheuristic which it can perfectly solve even for a very large network.

Therefore, the qualities of PPG results can be tested by performing the optimization shown, where the ILP optimizer is able to produce the best results possible with the augmented traffic produced by the PPG and the ILP generator which is taken to be perfectly correct and enables to obtain a measure of the PPG quality by comparing the optimized deployment cost with the known optimal result.

Emperical Evaluation of Matheuristic (SAN + SAL) Algorithm

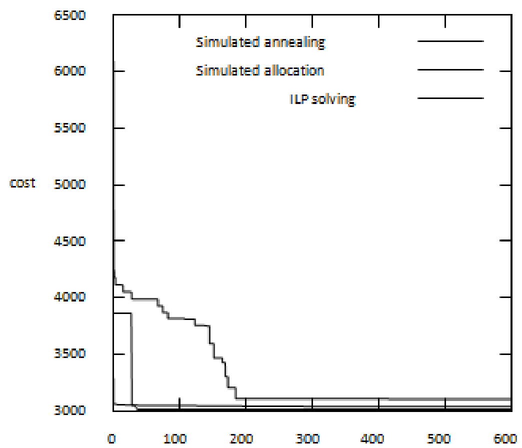
Comparing the two designed network programs, the results in both cases depend only on the network and the augmented traffic. As the ILP solver is only able to produce optimal results if the problem size is not too large enough. If the ILP generator is assumed correct, we can assess the qualities of the simulated annealing and allocation heuristics by comparing the results of the two methods.

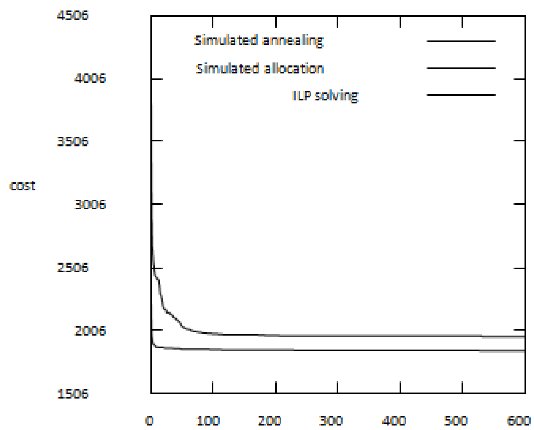
The networks used in the experiments are two real world examples of networks in Nigeria, National network and C –net network. For each network, up to 3 mutually disjointed shortest paths and up to 5 shortest paths are generated for each pair demand nodes. Each (task-network-wavelength-method) configuration is run five times for 10CPU minutes on a 550MHz HP series 9200 model J9000 with 2.5Gb RAM per optimization process. The results are shown below.

Table 6: Comparison of the three optimisation methods

Task	*Net*	*W*	*Simulated allocation*		*Simulated annealing*		*ILP solving*	*status*
ND	A	4	444.00	0.00	444.60	1.79	444.00	Optimal
		16	413.00	0.00	415.20	0.89	413.00	Optimal
		256	404.00	0.00	404.00	0.00	—	Timeout
	B	4	4384.40	1.49	4453.50	19.12	4377.68	Optimal
		16	3035.02	3.26	3103.25	13.33	3010.46	Optimal
		256	2605.78	1.01	2674.70	6.96	—	Timeout
	C	4	2053019.09	19371.23	2089457.59	144781.07	2847760.00	Timeout
		16	1898782.67	4598.40	1979889.76	97755.62	—	Timeout
		256	1842618.71	4984.74	1954155.21	55768.88	—	Timeout
TRP + PDP	A	4	579.00	0.00	589.00	1.41	4377.68	Optimal
		16	531.00	0.00	537.00	1.41	—	Timeout
		256	515.00	0.00	516.80	1.67	—	Memout
	B	4	9614.92	7.15	9667.46	11.70	4377.68	Optimal
		16	6074.30	3.74	6083.91	4.15	—	Memout
		256	4935.40	0.96	4948.83	3.11	—	Memout
	C	4	3604097.35	32069.91	3705365.99	28938.54	4377.68	Optimal
		16	3341704.02	14458.96	3409685.70	48311.27	—	Memout
		256	3246105.29	33566.56	3315111.54	65634.92	—	Memout

The status "optimal" indicates that the ILP result is proved well optimally, while "timeout" or "memout" indicates that the optimization process is terminated when the time or memory limit is exceeded respectively. The graphs in the figures below





show the progresses for the optimal best solution recorded during network enhancement or optimization as a pointwise average percenatage.

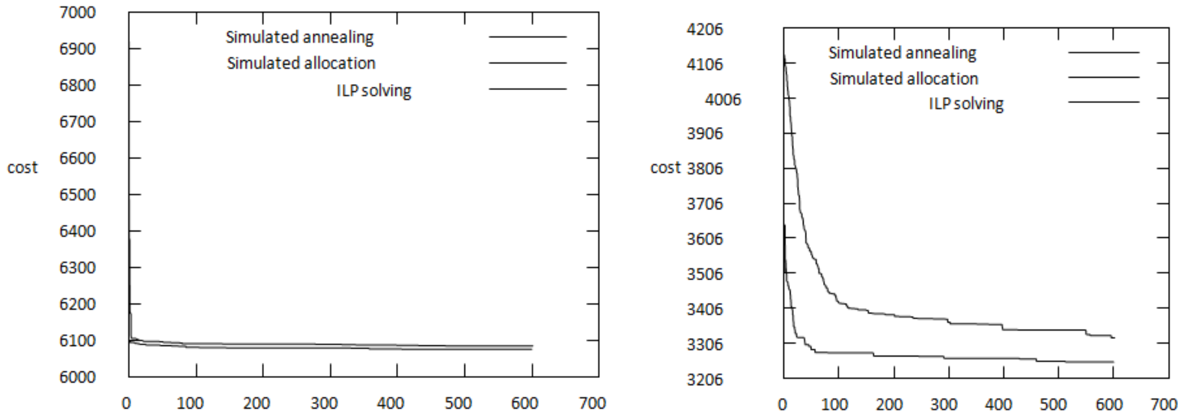


Figure 7: Solution cost progress on matheuristic

The results indicated that simulated allocation is slightly better than simulated annealing because of its percentage increase and fast response though both of the methods are really good. Furthermore, it obtains almost optimal results in the case where the ILP solver reaches a result within the time limit. Therefore, with all these proofs, optical network protection could be raised.

Table 7a: Simulation data for wavelength used, (a) National network (b) C-net

WLL	300	350	400	450	500	550	600	650
NWL	65	70	75	80	85	90	95	100

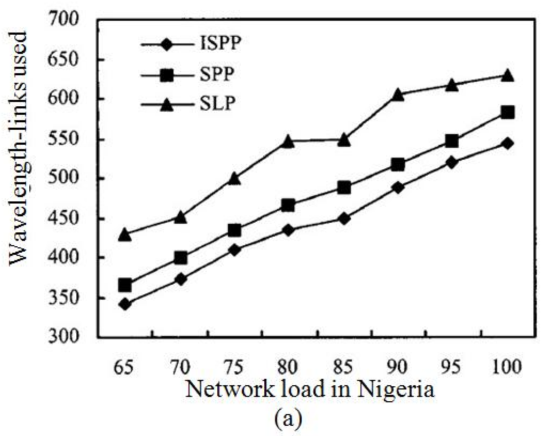


Table 7b: Simulation data for wavelength used, (a) National network (b) C-net

WLL	350	400	450	500	550	600	650	700
NWL	65	70	75	80	85	90	95	100

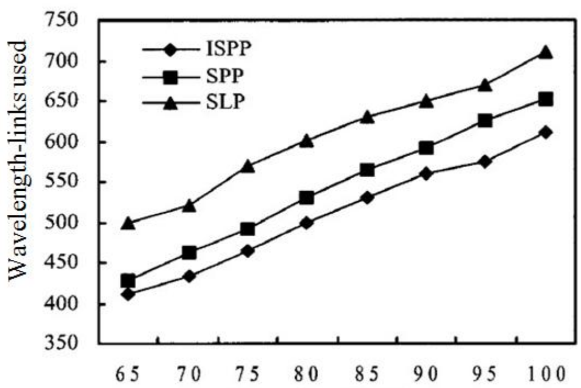
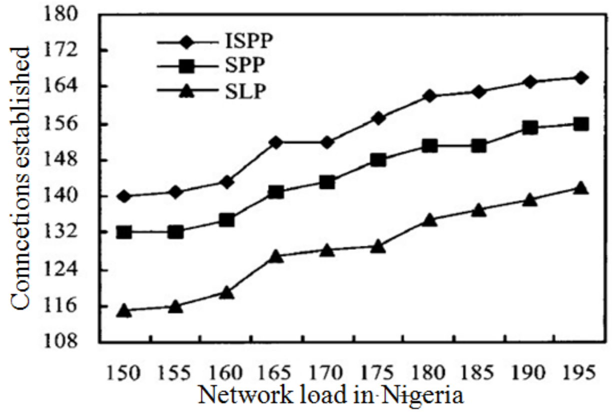


Fig.8: wavelength-links used for ISPP, SPP, and SLP in (a) national network and (b) C-net.

Table 8a: Connection establishment data (a) national network (b) C-net

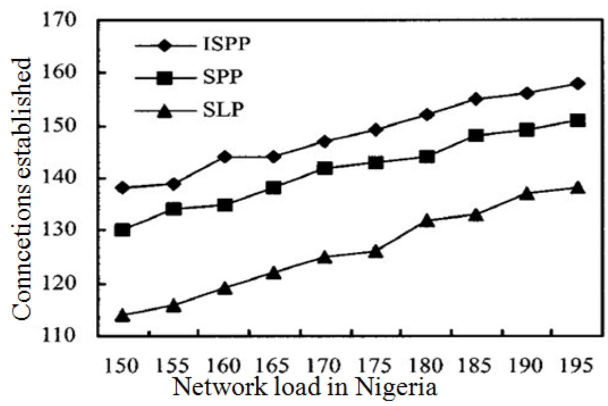
CE	108	116	124	132	140	148	156	164	172	180
NWL	150	155	160	165	170	175	180	185	190	195



(a)

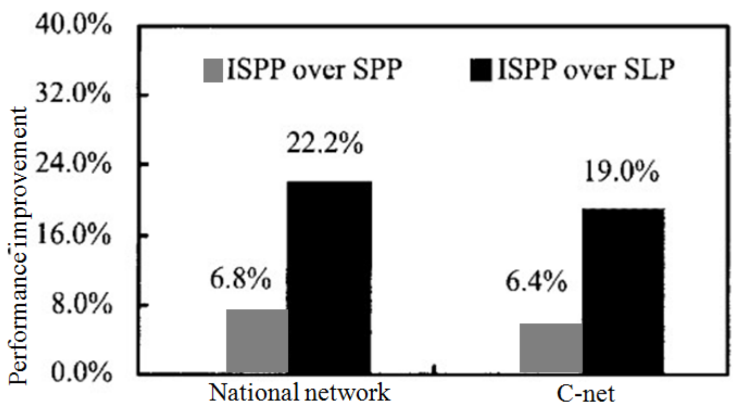
Table 8b: Connection establishment data (a) national network (b) C-net

CE	110	120	130	140	150	160	170	180	190	200
NWL	1	155	160	165	170	175	180	185	190	195

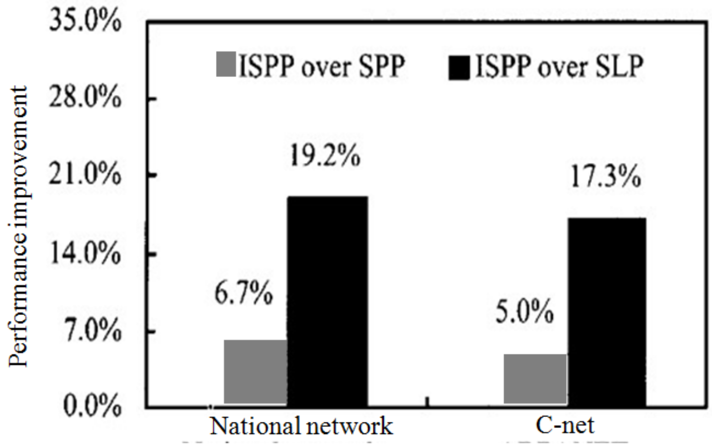


(b)

Fig.9: Connections establishment for ISPP, SPP, and SLP in (a) National networkand (b) C-net.



(a)



(b)

Figure 9: performance improvements of ISPP over SPP and SLP (a) Resources utilization ratio and (b) connections establishment.

IV. CONCLUSION

The design tool was extended to include the nodes as an integrated part of the optimization, using a second degree polynomial for modelling node costs. Experiments showed that the tool was able to reduce overall node cost with up to between 20% to 30% in some cases of the nominal design task, while the tool was able to achieve significant results for the protection design. However, for the node costs, introducing a multigranular optical switch model that reduces the sizes of the switch matrix by grouping and switching wavelengths in bands of fibres. The novel algorithm, subpath wavelength grouping (SWG), is able to optimize a multigranular network for both link and node costs by routing in an unorthox way; starting with common subpaths instead of individual connections. Empirical evaluations showed that compared to previous methods SWG is effective at reducing costs, especially when link cost are relatively higher than node port costs.It was considered as well thatthe problem of subdividing wavelengths into timeslots match the data transport granularity with the traffic demand granularity. It was noted also that designing a wavelength and time-slot routed optical network is equivalent to designing just a wavelength routed optical network with more wavelenghts and further that wavelength or timeslot conversion and timeslot delay had no effect on the wavelength usage in the network. Furthermore, it was shown that optimising shortest path routing is good at minimising wavelength usage when using a hop-distance metric.

In furtherance of the research, the popular MS-SPRing networks was analysed, constructing an ILP model as an arc-flow model augumented with constraints modelling the rings. It was shown that a real world ring network designed by a human network planner could be designed at a cheaper cost by running the model through ILP solver. The lesson learnt was to consider using a lot of rings of various sizes, rather than using few rings with ring interworking. Moreover, it was found that comparing a real world prices that network switch prices must be reduced by approximately between 40% to 45% if they are to compete on cost with the MS=SPRing networks.

The studies showed that when there is no delay and traffic demands are of similar sizes, the call blocking is chiefly determined by the offered loads on the links that the demands use. When the setup delay is larger, the blocking probability is determined by the number of hops. It was also found that node delay yields higher blocking probability than the corresponding link delays. Considering reservation strategy, the single wavelength reservation generally gives lower blocking probabilities except for longer paths that might benefit from being able to reserve several wavelengths on first hop of their paths.

We had extended the basic model of the algorithm to include multifibre links, and made some empirical studies which showed that shortest path, generally experience lowering blocking when no wavelength converter is used, but longer paths have a little bit of blocking though the difference is very insignificant. Only in some special cases, they do experience a relatively blocking increase of about 2%.

Therefore, this work has thoroughly investigated recovery mechanisms for double-link failures in WDM networks. Recovery processes require three entities; fault-detecting, fault-reporting and fault-deciding for survivability of the system. Protection paths may be pre-computed or provisioned on demand. In either case, the protection paths may be dedicated, shared or mixed-shared. Futhermore, several link and path protection schemes were described and qualitatively compared by considering in addition to spare capacity requirements of other parameters such as signaling requirements or flexibility against changing traffic patterns. It was shown that a lot number of parameters such like topology, technology or traffic patterns influence the performance of network design and that there are complex relations between the parameters. A proposed path protection scheme using ring covers turned out to be very efficient and signalling complexity is made low. It has been noticed that selection of a specific protection strategy for a network does not only depend on the efficiency the scheme, but also on many other parameters such as signalling requirements, restoration time/speed, flexibility, granularity, length increase and sharing factors.This work has studied and proposed a new failure protection algorithm called ISPP. Compared with the previous SPP and SLP techniques, ISPP allows the primary paths and the backup paths to share the mixed wavelength-links based on the proposed new rules in which some primary wavelength-links can be changed to mix wavelength-links and can as well be shared by primary paths and backup paths. Some mixed wavelength-links can also be shared by different backup paths for saving resources, high utilization and blocking probability reductions.Noteably, ISPP algorithm gives better performance than the conventional SPP and SLP algorithms. Therefore, Self healing ring implementations are promising step towards a better optical network protection due to reduced realisation complexity.

Hence, in the overall summary, it is concluded that the goals setup in the introduction of this work have been met, and has fulfilled the objectives of contributing to the models of computer asisted network plans of the protected network. However, it is natural that no matter how much ground any research might have covered, there must be a few new and intriguing unanswered questions that may remain in the minds of reviewers and other users of that work. In leu to that, it is interesting that some of the few notable issues are listed as recommendations for further research interests.

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