
Research Projects and Problems

A web-based addendum to the book:

Mesh-Based Survivable Networks:

Options and Strategies for Optical, MPLS, SONET

and ATM Networking

version 1a, February 20, 2004

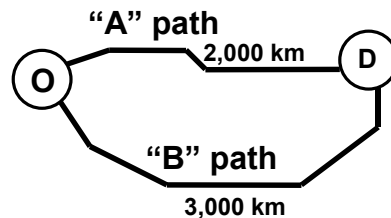
- 1 What do you think about McDonald's proposal to measure the impact of network outages with the "ULE"? Comment and reason about the following based on your own experience and technical background:
 - a. Would the societal impact be logarithmically or directly proportional to the 'magnitude' of the outage?
 - b. What do you suspect statistical frequency versus the distribution of ULE magnitude might look like? Give some line of reasoning based on physical or statistical principles.
 - c. What would be the main advantage of a ULE type measure as opposed to availability measure? (i.e., in what sense does availability fail to reflect the actual impact of outage on customers?)
 - d. Can you suggest an adaptation of McDonald's proposal to reflect impact via connectionless services (e.g., TCP/IP applications) as well as Erlang-oriented traffic, or, propose your own alternate overall impact measure for telecommunication network outage.

- 2 In your view, what would be examples of applications or services that might be well served by the following restoration times, especially if the user cost was in proportion to the restoration speed:
 - a. 30 min
 - b. 60 sec (1 min)
 - c. 1.5 sec
 - d. 50 ms
 - e. within a single bit time, i.e., "hitless" switching

- 3 In one sense, it seems rather self-defeating that network switches drop all connections in progress after about 2 seconds of outage on the associated carrier facilities. Can you think of reasons why this might be technically necessary? Also, if a call-dropping event occurs following a major cable cut, what might happen to the network shortly after as the indirect effect?

- 4 With the discussion of Causes of Failure (p. 103) in mind, comment on the following imaginary instructions in a user manual intended to walk a craftsperson through the steps needed to create a new cross-connection in a DCS machine:
- (i) retrieve a blank cross-connect map file from the User/Accessories/ folder
 - (ii) identify the first and second DS3 port name/numbers to be cross-connected in the scroll-down selection lists.
 - (iii) enter the confirming password codes to save the new DCS core cross-connection map file.
 - (iv) to put the new cross-connection into effect log in as system operator and assert the new map file onto the DCS core matrix.

- 5 A 1:1 diverse-routed APS arrangement is established for a certain transcontinental STS-1 demand pair. The working path (“A”) is 2,000 km long and the protection path (“B”) is 3,000 km long. Over 5 years of operation there are 10 isolated failures on one or the other of the diverse “A” and “B” signal paths. In three of these the APS switches over successfully after 50 ms and a 10 ms outage is experienced when the signal was switched back to the working path. In six of these no outage is experienced. In one of the cases, however, the “A” signal feed is cut while some equipment along the B route was out of service for maintenance. This resulted in a 30-minute service outage before this was discovered and corrected. The failure rate for each path is proportional to the length of that path and the failure rate per km is the same for both paths.



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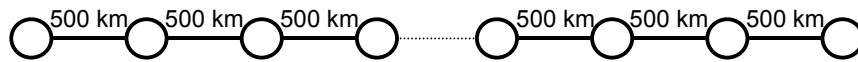
- (a) Assuming the average MTTR for the 10 failures to be physically repaired is 4 hours, what is the actual availability of each path on its own?
 - (b) Based on (a), what would be the theoretically expected service availability for the whole 1:1 APS system?
 - (c) Estimate what would be the availability of the system if the protection path length was 4,500 km.
 - (d) Now based on the given data, what was the actual availability of the service over the five-year period?
 - (e) In the actual availability (from (d)) comment on the relative contributions to unavailability of the three successful APS switchovers (with 60 ms total outage each) and of the one 30 minute outage event. What insight does this give you about the kind of failure scenario we are most likely to consider in doing availability analysis of redundant protected transport schemes in general?
 - (f) An issue in 1:1 APS systems is whether a signal should be switched back to the working path after repair of the failure that caused the signal to be switched to protection. The alternative solution is to leave the signal on the protection path, which in fact becomes the working path and the working path becomes the protection path. Comment on the implications in terms of system availability of such a solution.
- 6 Hypothetical Reference Digital Path (HRDP) Analysis: Background: An HRDP is a “near worst case” path model used for network planning purposes such as:
- (i) To allow calculation of an estimated availability on a reasonable or representative model of the worst-case path design any customer may experience, based on network topology and

measured or forecast data for the availability of individual equipment items and subsystems in the path.

(ii) To permit “working backwards” from an end-to-end availability target for the HRDP so that unavailability allocations may be made for the design of new elements to be deployed in the network.

(iii) To assist in new technology and/or network strategy selection, i.e., to be able to assess the availability benefits of various topology changes and/or adoption of new restoration techniques for example.

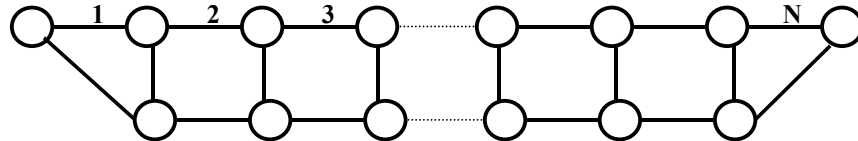
(a) Prior to ~1990, the “Telecom Canada” HRDP for a 'worst case' coast to coast digital service path was a simple linear model with 10 spans.



If the end-to-end availability is to be $3 \times 99.95\%$, and transmission was primarily radio-based with $U_s = 1.5 \times 10^{-9}/\text{km}$, then what is the maximum allocation for node unavailability, U_n ? What is this in min / year? (Assume 1 year = 8766 hrs)

(b) If planners foresee an evolution to all-fiber transmission but expect a 20-fold (i.e., 20x) increase in U_s due to cable-related outages relative to the prior radio-based U_s , then is it feasible to meet the end-to-end HRDP objective by requiring improvements in U_n ? If so, what is the new requirement for U_n ? Comment on the possible implications (cost? economical?) of requiring a reduction in U_n of this magnitude.

Now consider a different network topology. A proposed alternative is to adopt active restoration re-routing and reflect the route diversity options for each path through a revised “ladder network” HRDP.



(c) Recognizing now that any single failed span or node (except the 2 end-nodes) can be re-routed around, derive a general expression for the availability of a path through the above HRDP in terms of U_s (unavailability of a span/km), U_n (unavailability of a node), and N ladder sections. Also assume that each reconfiguration requires 2 hours for a node-failure and 1 minute for a span-failure while physical repair (node or span) takes 12 hours (i.e. MTTR values). (Hint: Find unavailability due to single failures, then unavailability due to dual-failure combinations and finally compute the total availability.)

(d) Using your result from (c), what is the new HRDP availability using the fiber $U_s = 3 \times 10^{-8}/\text{km}$ and U_n from (a)? To allow comparison with results for the first HRDP topology use $N = 10$ and the same span length of 500 km for each span. Comment on the unavailability results from the “ladder HRDP” and the original “serial HRDP”.

- 7 Assume that a local exchange carrier has 10,000 subscribers, each of which generates 2.5 calls per hour, on the average. At some point, all subscribers lose dial-tone for two hours. What is the (U, D, E) triple description of this service outage?

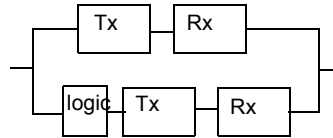
- 8 Derive a simple expression for the network average nodal degree of a network in terms of the number of spans S and nodes N . What property of transport network graphs are you inherently relying upon in obtaining this result?
- 9 Outline the design of a computer program that will take as input a collection of nodes, their (x,y) coordinate locations, and generate a plausible demand pattern for study purposes. It should allow a user to reflect any balance of a baseline of uniform random demands, a hubbing component and a gravity-like tendency between nodes that are over a certain threshold distance apart. Allow the user to input a target total volume of demand units and scale everything (within integer feasibility) to approximate the total demand target.
- 10 Using the “Erlang B” formula (or suitable traffic tables) what is the percentage increase in offered traffic required to drive blocking from 1% to 20% in (a) a group of 15 trunks, (b) a 150 trunk group. What general insight does this give you about circuit-switched services layer restoration methods? The Erlang B formula is given below. A =offered traffic in Erlangs, N = number of trunks, $B(N,A)$ = blocking probability:
- $$B(N, A) = A^N / \left(N! \sum_{i=0 \dots N} \frac{A^i}{i!} \right)$$
- 11 Consider a physical layer network of N nodes that is realized as a ring, i.e., the physical topology is a closed set of degree-2 nodes. On top of this a full-mesh of logical trunk groups is established between service layer switching centers (i.e., each node has direct trunk groups to every other node). Derive an expression for the number of simultaneous logical trunk group failures arising from any one physical span failure as a function of N . State clearly any assumptions about routing to realize logical trunk groups. Discuss the extent to which this result could serve as an upper bound on the failure escalation factor in more general physical and logical layer topologies.
- 12 Show from basic combinatoric analysis or using the availability analysis methods of Chapter 3 that system availability for a $k:N$ APS arrangement is higher than if the same number of protection and working channels are arranged as $k I:N$ sub-groups. On the other hand, what extra equipment design and control complexity considerations arise for implementing $k:N$ APS. If the line-switched signal is in the very high Gb/s range can you think of what extra electrical design challenges also arise with the $k:N$ APS ?
- 13 Define a GOF type measure for “node restorability” of a node x . First some consideration is needed of what it is possible to “restore” by any network-level rerouting action in the event of a node failure. Specifically, demands terminating or originating at the failed node cannot be restored per se. Thus our measure should consider only transiting demands. In addition we will stipulate that our failure scenarios are every individual node failure, assuming total interruption of every demand flow to, from or through the node. A GOF-type measure of node restorability could then be defined as:

$$R_{node, x} \equiv \left(\sum_{\forall (i,j) \in D, i \neq j \neq x} \min(d_{i,j}, k_{i,j}) \right) / \left(\sum_{\forall (i,j) \in D, i \neq j \neq x} d_{i,j} \cdot \delta_{i,j}(x) \right) \quad (0.1)$$

where D is the network demand matrix, $d_{i,j}$ is the number of demand units exchanged between nodes (i,j) , $\delta_{i,j}(x) = 1$ if the routing of $d_{i,j}$ includes node x , and is zero otherwise, and the range

specifications on the summations exclude consideration of demands originating or terminating at node x itself. Finally, $k_{i,j}$ is the number of network-wide replacement routes available for restoration of $d_{i,j}$ in the post-failure network.

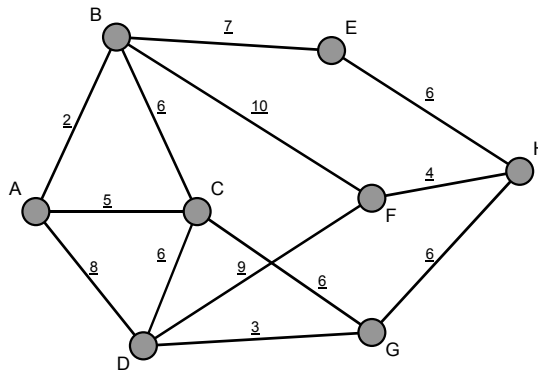
- 14 Show that with a constant failure rate the probability of one failure in $[0,t]$ is identically the reliability function $R(t)$ for the same case.
- 15 If a system of two CPUs are arranged with internal switchover when one fails then what is the reliability function for the pair as a system in terms of the reliability function of one processor alone?
- 16 Based on the definition of availability, what is the (long term) availability of any physical system that cannot be repaired?
- 17 Can a purely parallel availability relationship ever really exist between subsystems? (Think about the joining points in Figure 3-19.) Can you think of physical examples of nearly perfect parallelism and other cases where the sensing, switchover, or joining node is a much more significant factor.
- 18 Consider the redundant high speed (HS) transmit-receive subsystems in the at the right where the protection switching control logic is represented as part of the protection system. What does this recognize? Develop the system availability model.



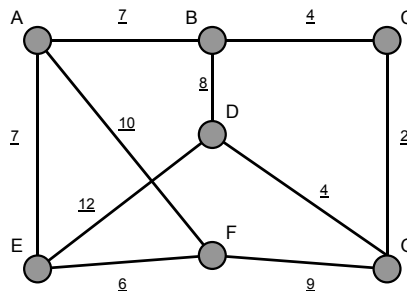
- 19 Work out a specification for (identical) head-end bridge and tail-end transfer relay maximum switching times so that a complete APS switching time of 50 ms is met in response to the sudden (test case) onset of 10^{-4} BER in an OC-48 system based on the following assumptions: (a) STS-48 frame time = 125 μ sec; (b) signal fail (SF) generated after 10 consecutive errored-milliseconds; (c) three frames to validate any K1, K2 byte change; (d) 1 ms processor time for response to any K1, K2 signalling or SF event. For a worst-case specification, assume a strictly serial (time additive) event sequence but identify where certain elapsed time intervals would actually be happening concurrently. State any other assumptions.
- 20 Design a finite state machine (FSM) that implements the Sonet K1-K2 byte APS protocol. Show the entire FSM for both head-end and tail-end functions at one end of the system.
- 21 Given the relatively high demand for line-overhead bytes for different uses in the Sonet standard, why do you think standards organizations were willing to allocate two bytes for APS signalling as opposed to leaving the APS signalling function to be implemented within the line-level DCC channel?
- 22 In the process of reversion in an APS system the controller deactivates its local tail end transfer relay *before* releasing the upstream head end bridge. What is the effect of doing these operations in the reverse order?
- 23 Construct a small example network which illustrates that the shortest path plus the next short-

est disjoint path between O-D nodes (“method a”) is not equivalent to the shortest pair of disjoint paths (“method b”). Can you find a construction in which “method a” is not even feasible while “method b” is? Is the cycle with shortest circumference that contains both O and D equivalent to “method b”?

- 24 Using a cut-set style of combinatorial failure analysis, compare the average (per-system) availability of capacity equivalent systems: (a) two groups operated at (1:7) APS, (b) one group operated as (2:14) APS. Develop analytical models, compare them through functional analysis and numerically.
- 25 Dijkstra's algorithm: In the network below, consider the edge weights to be distances.



- a. Using Dijkstra's algorithm, find the complete shortest-path tree from node F to all other nodes. For each step of the algorithm show which nodes receive temporary or permanent labels and the updating of temporary labels.
- b. Based on the same network or on another network can you construct a case that shows why it is important that the next permanently labelled node is not necessarily one of the nodes just scanned in the current iteration?
- 26 All distinct routes: In the following network the edge weights are numbers of working links on



each span.

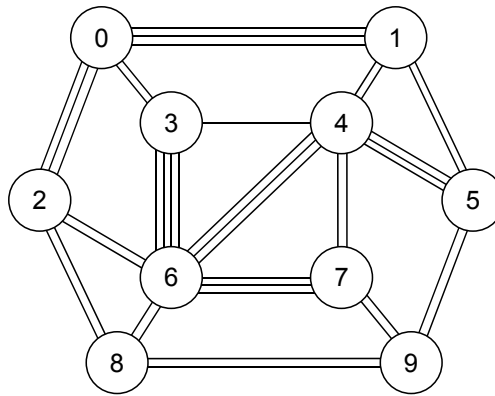
- a. Develop a depth-first search tree to find all distinct routes (to a hop limit of 5) between

nodes (A-E) and (C-G) (excluding the direct spans.)

b. Write an expression for total spare capacity on all spans as a function of the restoration flows assigned to each distinct route for each of these two possible failures.

c. Working by inspection (or numerical iteration), can you find an allocation of restoration flows to the distinct routes available for restoration of spans (A-E) and (C-G) that yields the least total spare capacity required on all spans?

- 27 K-shortest paths: Working by hand, on printed (or electronic) copies of the following “reserve” network diagram, find the maximal k-shortest paths restoration path-sets for spans (0-2), (3-1), (8-6), (2-8), (1-5), and (3-7). For each case show a highlighted overlay of your path-set and note beside it: the total number of paths found, whether restoration is end-node limited or not, and whether the ksp path-set equals max flow capacity or not. Also, show the corresponding min-cut on each diagram.



- 28 Formulating Network flow as LP / IPs: This problem uses the public domain `Lp_solve` software available at the book's website. Installation and running instructions follow. Problem: Consider the following “reserve” network after a span failure between nodes 1 and 5. The net-

work is given in adjacency list form:

Node	Node	Capacity	Distance
1	2	13	10
1	3	4	5
2	3	3	7
2	5	5	15
2	4	12	6
3	5	8	4
3	4	9	17
4	5	7	8

- Write and solve a formulation for the maximum flow between nodes (1-5) as a “transportation” type problem for the assignment of directed flows to each span. Why is it particularly important to represent possible flows in both directions on spans in this approach? Does the solution change if the problem is run as an LP or IP?
- Write and solve the corresponding formulation for max flow as an assignment of flow values to all distinct routes between nodes (1-5). Is the result equivalent to that of (a)? Should it be? Comment on the relative number of constraints and variables involved with each approach. What other advantages / disadvantages can you see for each approach?
- Adapt either method to solve specifically for the set of eight (8) restoration paths that has minimum total length.
- Do the results in (a) or (b) differ in any important way from those found by k-shortest paths running on the same data? How does ksp compare in finding the globally shortest set of eight paths?

To run `lp_solve`, unzip the distribution file to a new directory, prepare your input problem file (*.lp) with a text editor and save it with a .lp extension. Put the *.lp file in the directory with `lp_solve`. Then open a DOS command window, go to the directory where `lp_solve` is and run `lp_solve "<" input file ">" output file`. Example: `lp_solve < prog1.lp > prog1.out` The syntax for *.lp files is:

Objective function: $\max: f1+f2+f3+f4$; or $\min: 15 c1 + 7 c2$;

Constraints: $\text{node1: } x12 - x23 - x25 = 0$; or $\text{span4: } f1+f5+f8 \leq 17$; or $x1 + x2 + x3 < x7 + x5$;

Integer declarations: `int x12, x13, x14`

There is more documentation and syntax examples in distribution files.

- Write a program to implement the mathematical test for whether a given IP tableau is unimodular or not.

- 30 Develop an explanation linking the mathematical definition of unimodularity to the intuitive explanation of certain problems being “trapped on discrete space” given discrete RHS constants. (i.e., intuitively, what is the effect of every square submatrix having ± 1 or 0 determinant?)
- 31 Consider the problem: $\max (11x - y)$
 subject to: $10x - y \leq 40,$. Solve it as an LP and then as an IP.
 $x + y \leq 41/2$
 What does this example illustrate?
- 32 Consider the following “reserve network” of spare capacities after a span failure between nodes 1 and 5. The network is given in *adjacency list* form:

node i	node j	capacity	distance
1	2	15	10
1	3	3	5
2	3	3	7
2	5	3	15
2	4	10	6
3	5	7	4
3	4	6	17
4	5	5	8

- (a) Draw a capacitated network graph from this data.
- (b) Write and solve a formulation for the max-flow between nodes (1-5) using LP_solve. Why is it important to define flow variables that represent possible flows in both direction on each span? Does it make a difference if the problem is solved as an LP or IP? Provide a construction of individual paths between (1-5) consistent with the max-flow value obtained and the x_{ij} 's of the solution.
- (c) Adapt your formulation to solve for the specific set of eight restoration paths between (1-5) that has minimum total length.
- (d) Suppose a second failure arises, on span (3-4). Explain why a multi-source MCNFP formulation with nodes 1 and 4 as sources, nodes 5 and 3 as sinks, is *not* an appropriate model for the required two-failure rerouting problem.

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- 33 Repeat the application of Dijkstra's algorithm to find the tree of shortest logical hop distances from node A to all other nodes in Figure 4-11.
 - 34 Create adjacency matrix, incidence matrix, and adjacency list representations of the graph in Figure 4-11.
 - 35 Use a plotting package or program of your own means to produce a family of equi-redundancy contours of Eq. (5.38) in the (positive only) plane of nodal degree versus the peak-to-average w_i ratio ξ . What further insights and interpretations can be made from this?
 - 36 In section 5.3.4 a depth first search procedure is outlined to obtain all distinct routes between two nodes. The procedure is executed by Herzberg and Bye once for each failure scenario to generate the eligible route set for restoration of that failure (i.e., S independent calls to `all_distinct_routes`). Can you devise a more efficient procedure to populate all of the P_i route sets needed for formulation SCA (arc-path) based on the general observation that while searching for one $\{s,t\}$ pair, all or parts of eligible routes for other $\{s,t\}$ pairs are obviously also being traversed? Suggestion: consider the information embedded in a set of all simple cycles of the network graph. Why could the alternate approach be especially useful in an extension of SCA (arc-path) to path restoration?
 - 37 Continue the example from section 5.3.7 in two ways: (a) develop and solve the corresponding set of cut-set constraints for capacitation of the network shown for restorability of span (4-5) alone (as if it was the only span to be protected), (b) *add* the constraints pertinent to span (4-5) to the existing set for span (1-2) and solve the complete system for min spare that fully restores either of the two spans. Assume $w_{4,5} = 20$. Compare and discuss the two individual-failure capacity designs to the merged single solution problem. What insight does this give you about the nature of the SCP problem?
 - 38 Give examples of some partial cutsets that the `simple_cuts` procedure in Figure 5-12 does not produce. How many partial cutsets are there in total for each failure span?
 - 39 Show that in addition to the added constraint developed from the incomplete restorability of span 5 in the example of Figure 5-15 and 5-16 spans 3, 0 and 1 will similarly contribute the added constraints $s_6 + s_0 \geq w_3$; $s_6 + s_3 \geq w_0$; $s_6 \geq w_1$.
 - 40 Write and solve the complete tableau for the example of Figure 5-15 at the end of the first LP stage after addition of the four additional constraints discovered with `Lp_solve`. Is the network fully restorable at this stage? If not, find the added constraint(s) at this stage and effect one more iteration. Check for completion of the design. (Hint: Total sparing of the completed design is 14 spare links.)
 - 41 You may note that following addition of the four constraints above and execution of the LP for the second iteration, that the total spare capacity remains unchanged from the first iteration at 11 total spares. Explain this.
 - 42 Based on comments on section 5.4.2, construct a capacity-weighted example network where the actual redundancy is lower than $1/(d-1)$. Do you think this would happen in practise on a real transport network?

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- 43 Develop and test the hypothesis that a bound on the spare capacity requirement of a path restorable network can be obtained from a corresponding span-restorable capacity design in which any loopbacks in the resulting end-to-end paths under each failure scenario are found and deleted. Is the resulting capacity estimate provably a lower or upper bound on the path-restorable spare capacity? What effect tends to be overlooked or oversimplified in the idea that loopback capacity is the key inefficiency in span restoration relative to path restoration?
 - 44 A path restoration mechanism makes no basic distinction between single or multiple span-failure scenarios. Does this imply that there is no further benefit or incentive to minimize or eliminate SRLGs in a network? Explain.
 - 45 In Figure 6-12, find at least three other node pairs for which it will also be infeasible to find a shortest and next-shortest disjoint path pair.
 - 46 Compare the number of constraints and variables, and types of variables, in SBPP-1 (p. 417) to those in `arc_flow_SBPP` (p. 425). Also compare the run times on selected problems. To what extent does `arc_flow_SBPP` seem to benefit computationally from its transportation-like problem structure?
 - 47 Make a further investigation of the technical issues surrounding stub-release and reversion following restoration with stub release. In what topology and/or demand situations would stub release make the largest difference in terms of capacity requirements relative to SBPP or path restoration without stub release? In a series of actual trial cases, what are the statistics and complexity of the “entangled routings” that are actually observed and would have to be sorted out in reversion?
 - 48 With reference to the results in [ShGr03] and the material of Chapter 6 in general, explain in more detail the basis of the speculation in the closing sentence of Section 6.1.4 about networks with node recoverability that do not need more spare capacity than for span restorability. Design and conduct an experimental study to validate this tendency. Either from first principles or experiments, on what type of graphs would it be less likely to be the case?
 - 49 Analyze and compare the complexity of OS-1, OS-2 and OS-3 formulations in terms of numbers of decision variables, capacity variables and number of constraints versus problem size. Characterize problem size by D , the number of relations to be served with a primary path, and by an assumed number B of distinct eligible backup route choices for every primary path (or eligible backup path option for OS-3).
 - 50 Study transient traffic issues resulting from shared backup path protection with oversubscription. How for instance does a TCP/IP session react to a sudden change in queuing delay as a result of restoration-induced oversubscription effects?
 - 51 Research the technical implications and requirements in both ATM and MPLS technologies of allowing primary path flows to be split over more than one backup path for restoration. ATM for instance provides a framework of VCs within a VP, VCs corresponding to the individual peering applications. It is tempting at first glance to think of VC-level rerouting over many fine-grained backup VC-like paths, but what actually would be required to support this? What

corresponding options would MPLS technology provide?

- 52 Extend the OS-1 formulation to a *multi-service environment* where each primary path service can be of three Quality of Protection (QoP) classes: (i) assured restoration with at least R' % bandwidth replacement, (ii) pure best-efforts replacement of failed capacity, (iii) preemptible. Preemptible service means that if required to satisfy the guarantees to class (i) services, these primary paths may be taken back for reuse of their capacity. No primaries are preempted to increase the best-efforts recover level however. An overall oversubscription factor of X_{tol} is not to be exceeded on any link.
- 53 Adapt the model above to a bi-criterion formulation where total spare capacity can be traded off against an increased measure of satisfaction of best-efforts service classes and/or a measure of the extent of preemption of class (iii) services.
- 54 Work out a modified KST-Alg that takes physical span failures into account when it routes backup paths seeking the minimal addition of new spare capacity for each backup added. First define the additional data structure(s) needed to represent physical-span to logical-link failure scenarios and the current shareability relationships on spare capacity. Then define a revised search procedure for backup paths that is guided by these data structures. Implement the modified algorithm and compare its total spare capacity requirements to that of OS-1.
- 55 Investigate the idea of routing primary paths over the physical graph of spans in ways that limit or otherwise control or mitigate the spare capacity needs when recovering by backup path protection at the logical link graph layer. An initial investigation could be to write a MIP formulation that chooses primary path routes in a way that minimizes the average number of primaries failed per span failure. A related exercise would be to study how the number of logical link failures per physical span failure varies with connectivity of the logical layer graph over a given physical graph. At one extreme each span failure causes on logical failure, but spare capacity for the logical layer backup protection may be high. At the other extreme, the logical layer graph is a full mesh and many links fail per span failure, but diverse backup paths are plentiful and short. Where in this continuum is total capacity minimized?
- 56 Consider a continental-scale network with 50,000 km of total route mileage. The average span is 300 km in length and failures due to all causes occur at a rate of 250 FITs / km. The average physical repair time is 18 hours. Work out the frequency of failures on the network as a whole and the total annual time expected to be in a state with at least one outstanding repair currently underway. How much time per year will be spent with two or more simultaneous failures on the network operators hands? You may assume each failure arising independently. State any additional assumptions needed.
- 57 If, under the conditions above, the network operator also schedules 4 hours a day of time for maintenance upgrades on existing transmission systems, then how often can one expect to be in a state where a span is down for maintenance and another span has failed?
- 58 In Section 8.6.1 it is asserted that single-failure restorability ($R_1=1$) is an inherent property of a network designed for $R_2=1$. Construct a simple proof argument to support this. Why do the single failure scenarios have to be explicitly asserted if *not all* dual-failures are specified? In practice, what difference might there be between the restoration path-sets for single failures in

a network designed for $R_2=1$ compared to one designed for $R_1=1$?

- 59 Conduct a study similar to that of Section 8.9 for the impact of SRLGs on span-restorable networks but for the SBPP scheme.
- 60 Make the required changes throughout the fixed charge and routing (FCR) problem formulation of p. 588 so that each O-D pair may have its own cost, c_j^r , associated with its flow across any given edge of the network. What might this represent in practise?
- 61 Why does it make sense in Figure 9-6 that both the absolute cost and the nodal degree at which minimum cost arises would be lower for the hub-like demand pattern than for a uniform demand pattern? (In the uniform demand model all O-D pairs exchanged exactly 5 demand units. The hub-like demand pattern was generated from the model $d(\text{hub to non-hub}) = 15 - \text{round}(\text{distance} / 50)$, $d(\text{non-hub to non-hub}) = 2$, where distance was taken as the Euclidean distance in the plane and the two highest-degree nodes were taken as hubs.)
- 62 Section 9.2.3 alludes to Kershbaum's explanation that routing alone is $O(n^3)$ as a subproblem in determining overall topology. What do you infer he is taking into account in this statement and to what extent could this complexity be reduced?
- 63 In Section 9.6 a short-list of promising single-span addition candidates are identified for detailed capacity-related cost benefit analysis by re-running SCP or JCP in the presence of the augmented topology. One of the implications of this is that, considering JCP, the sets of all eligible working and restoration routes have to be re-generated or preferably in some way just *updated*. Thus, consider the following problem. A set of eligible working and / restoration routes are initially obtained for a graph G . One new edge is added (or deleted) from G , creating G^* . Find an efficient algorithm to update the set(s) of eligible routes, without re-generating them from scratch for the G^* graph.
- 64 Project on single node topology expansion: Consider extensions or adaptations of the basic method of Section 9.6 to planning single-span topology additions to instead plan for the addition of a single new node being brought into the network topology. Assume a small number of new node addition candidates. For each, assume that a new row and column in the demand matrix is known and will be in effect if that node is adopted. Also assume that for each node addition candidate, the distance and cost of two new spans that will connect the node to the existing network are pre-defined. If a node is added, its demand is added to the network and the two spans associated with its addition become available for use in routing working flows and for restoration routing by the rest of the network as a whole.
- 65 Research project: Develop methods whereby the choice of an "optimum" topology somehow also considers future uncertainty in actual demand forecasts as well as actual future equipment costs. If two distinct topologies produced nominally the same total design cost, is there a way of secondarily deciding which one is preferable from a future-uncertainty standpoint? More generally, how would one find a specific topology that cost somewhat more under nominal conditions but given future uncertainty was in some sense a minimum expected-cost topology? Is simply have a bit too much connectivity relative to a strictly optimum solution to the nominal problem an effective form of future-proofing?

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- 66 A variant on the three-part heuristic in Section 9.9 is possible at step S2. This is to solve a *jointly* optimized mesh routing and spare capacity type of problem at this stage, with the same partially given topology from W1. The difference in the S2 formulation is analogous to that explained in Chapter 5 for adding joint optimization of working path routes to SCA (Section 5.4). This variation has not been pursued at present but would notionally trade increased run time in S2 for possibly improved solution quality in J3 (but this remains to be verified). If both variants are implemented, a further option is to form the union of all edges identified by W1 and each version of S2 as the edge-pool within which the J3 instance is solved.
- 67 With reference to sparse networks in Section 9.1, an interesting dimension of topology planning is the possible trade-off between the existence of span-SRLGs and average nodal degree. For instance, we might draw the nominal graph of physical spans for a network and it might (at least nominally) appear to be of fairly high average nodal degree. But what if one or more span SRLGs are actually present? Can we compute an “effective nodal degree” that recognizes the effect of span-SRLGs, if present, in terms of how they effectively degrade the mesh from its potential efficiency by virtue of the dual logical span failure situations they impose on the design. For instance the question could be: “Which is actually a more effective topology for mesh-based survivability: A very sparse topology (such as in Figure 1-14(a)) with *no* span-SRLGs, or the apparently richly connected graph of Figure 1-14(b) but with a set of span-SRLGs added to the nominal topology shown?”
- 68 Investigate whether there are unimodularity aspects to be exploited in PC-1 through PC-3 formulations. For instance in PC-1 and PC-2 the input quantities w_i , $p_{i,j}$ and $x_{i,j}$ are all discrete. Does this mean integrality need not be asserted on n_i ? Consider, test and explain whether any of these formulations has such aspects that may be exploited to reduce their solution times?
- 69 Is there a phenomena equivalent to the threshold hop-limit for span restoration, for p -cycles?
- 70 With reference to the two “forcer-clipping” heuristics on p. 779: Modify the second heuristic to involve a notion of significant forcers. Presently spans that are logically forcers, but with forcer magnitude of only 1 or 2 units are considered in the figure-of-merit for a forcer-clipping ring. The idea would be to apply a threshold of significance to the forcer magnitude before it is recognized as such. For example a threshold might be set at half the smallest capacity module available for an overlying ring. The forcer analysis program could be adapted to efficiently detect this binary status without a full determination of the absolute forcer magnitudes as for the first heuristic.
- 71 An open question in the forcer-clipping hybrid network design procedure of Section 11.6 has to do with a trade-off of using a larger working set size versus re-analysis of the residual mesh forcer structure after each ring placement iteration to maintain a smaller but continually updated and more targeted working set. With a large working set, there may be little need to re-analyze the forcer skeleton and the figures-of-merit for all cycles after each ring placement, but the large working set takes more time in the main evaluation loop. A smaller working set would make the main loop faster but may require regeneration of the working set after each iteration to yield quality results.

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- 72 Extend the basic methods of forcer analysis in Chapter 11, to discover and quantify significant *co-forcer* relationships among spans of the same cycle that is a candidate for ring placement. The idea would be to detect when the cycle unifies or collects together spans that co-force other spans in common. For instance, two spans may look like weak forcers individually (in the sense of (3.1)), but they are both strongly co-forcing some other span in common. In this case a ring that clips them off together should get the credit of their higher co-forcing magnitude, especially if the next latent forcer is much farther down.
- 73 As presently developed in a forcer-clipping ring-mesh hybrid, the working capacity that is moved from the mesh up to an overlying ring is simply displaced 'upwards,' without altering its basic route over the network graph. This pure capacity-displacement mode, is technically inferior to effecting a true loading of the ring with the demand segments that intersect it. In true 'ring loading' one considers the totality of demands whose routes intersect the prospective ring and solve an optimal loading problem to 'soak up' as much demand as possible, allowing the possibility of changing the routing of demands while they are within the ring. That is, one may legitimately detour a certain demand segment to go 'the long way around the ring' if it enhances the total demand serving capability of the ring. The entry and egress points of the demand segment seen by the mesh do not change in doing so, so there is no further complication in the overall algorithm. The only effect is that when a ring is being considered, it will generally be able to absorb more working capacity from the mesh by loading as opposed to simple displacement. The difference only matters BLSRs (not UPSRs).