Routing Algorithms

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Overview

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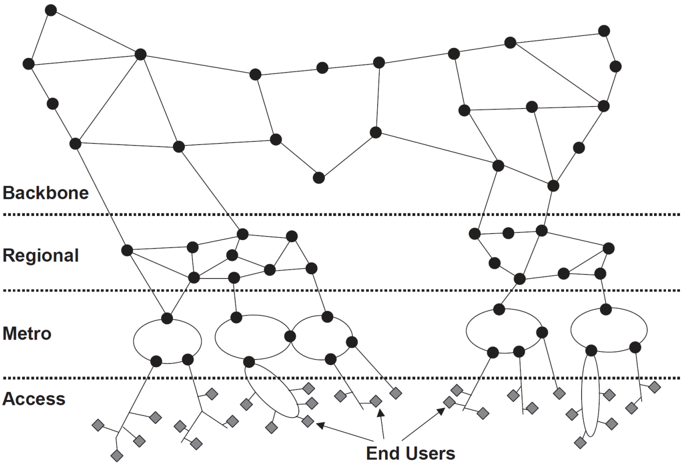


Figure: Routing is the process of selecting a path through the network for a traffic demand. Regeneration, wavelength conversion, protection, network type, network size, traffic matrix size, number of wavelength channels, ... affect the routing. The routing should take less than 100 ms in dynamic real-time network planning while the time is not a critical issue in long-term network planning. When the time is critical, a sub-optimal fast heuristic algorithm is used for the routing.

Routing Algorithms

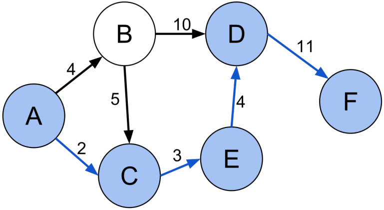


Figure: Most routing strategies incorporate some type of shortest-path algorithm to determine which path minimizes a particular metric. In the shortest-path algorithms, the metric is additive, i.e., for an end-to-end path is the sum of the metrics of the links comprising the path. Geographic distance, number of hops, and availability may be used as a metric.

Routing Algorithms

1. Dijkstra algorithm: is a greedy optimal algorithm that works for positive metrics.
2. Breadth-first-search (BFS) algorithm: finds the shortest path with the fewest number of hops and works for negative/positive metrics.
3. K-shortest paths (KSP) algorithm: finds K (disjoint) shortest paths between the source and destination
4. Constrained shortest-path (CSP) algorithm:
   1. Restricted shortest-path (RSP) heuristic: is sub-optimal and finds the shortest path under a single constraint
   2. Multi-constrained path (MCP) heuristic: is sub-optimal and finds any path satisfying all of the constraints, not necessarily the shortest path;

Routing Metrics

Minimum Hop

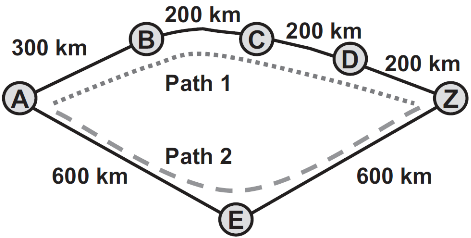


Figure: Path 1, A-B-C-D-Z, is the shortest-distance path between Nodes A and Z, but Path 2, A-E-Z, is the fewest-hops path. In an O-E-O network, where the signal is regenerated at every intermediate node, Path 2 is typically the lower-cost path. The minimum-hop paths can be found using KSP or Dijkstra algorithms by considering a metric of 1 for each link.

Shortest Distance

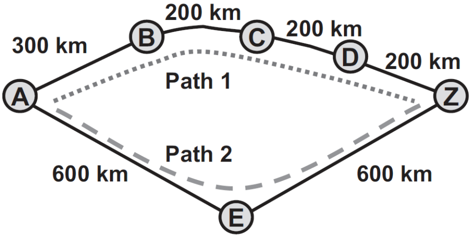


Figure: Path 1, A-B-C-D-Z, is the shortest-distance path between Nodes A and Z, but Path 2, A-E-Z, is the fewest-hops path. In a transparent network, where the signal passes optically every intermediate node, Path 1 is typically has a better optical reach and is proffered. The minimum-distance paths can be found using KSP or Dijkstra algorithms by considering the geographical distance as the metric of each link.

Minimum Required Regeneration

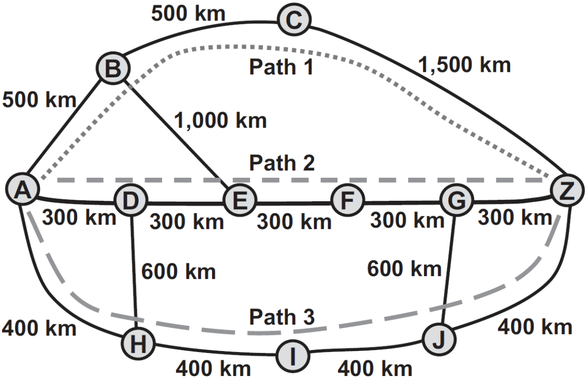


Figure: Assume that this is an optical-bypass-enabled network with an optical reach of 2,000 km. Path 1, A-B-C-Z, has the fewest hops but requires one regeneration. Path 2, A-D-E-F-G-Z, and Path 3, A-H-I-J-Z, require no regeneration. Of these two lowest-cost paths, Path 3 may be preferred because it has fewer hops.

Minimum Required Regeneration

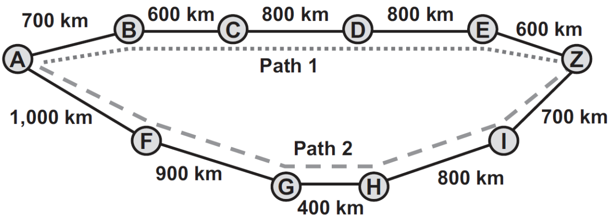


Figure: Assume that this is an optical-bypass-enabled network with an optical reach of 2,000 km. Path 1 is 3,500 km, but requires two regenerations. Path 2 is longer at 3,800 km but requires only one regeneration.

Routing Candidates

Shortest Path

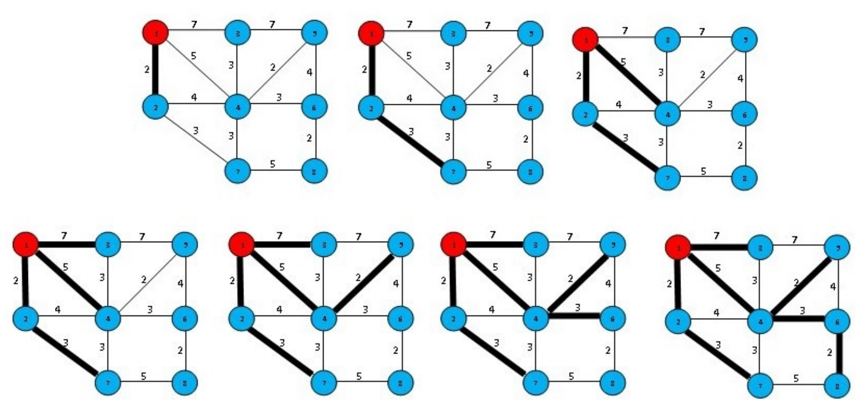


Figure: Dijkstra's algorithm to find the shortest path and shortest path spanning tree.

K-Shortest Paths

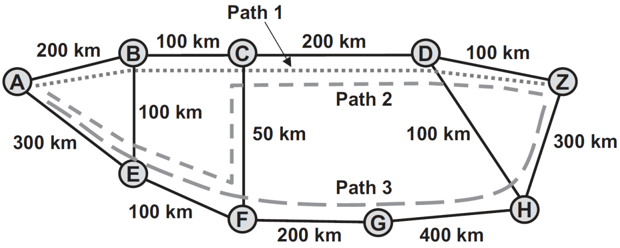


Figure: To find a set of lowest-cost paths in an O-E-O network or in an optical-bypass-enabled network without optical reach limitation, a KSP algorithm with the metric set to unity for all link can be used. In an optical-bypass-enabled network with optical reach limitation, a KSP algorithm can be run with distance as the link metric.

K-Shortest Paths

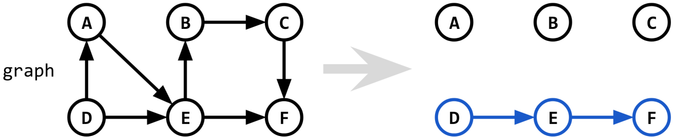


Figure: Yen's algorithm to find the first K shortest paths.

K-Shortest Paths

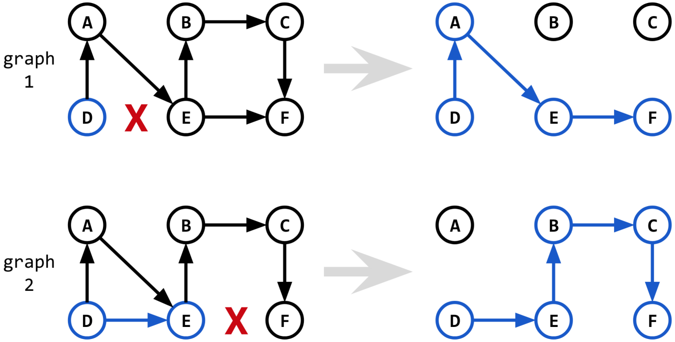


Figure: Yen's algorithm to find the first K shortest paths.

K-Shortest Paths

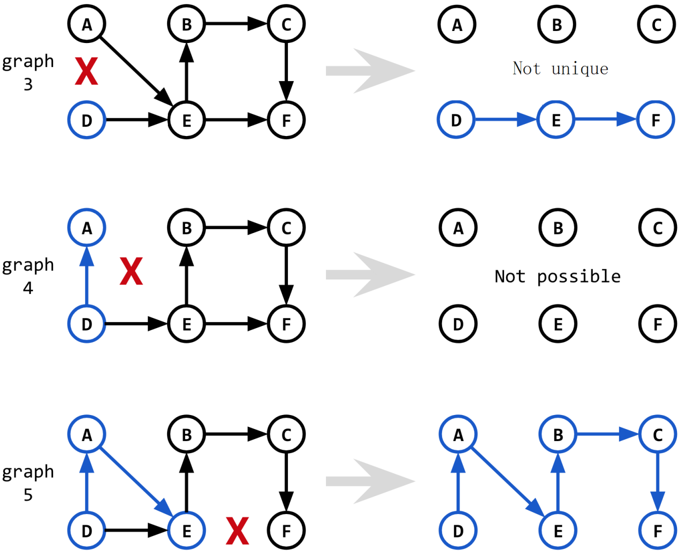


Figure: Yen's algorithm to find the first K shortest paths.

Bottleneck-Avoidance

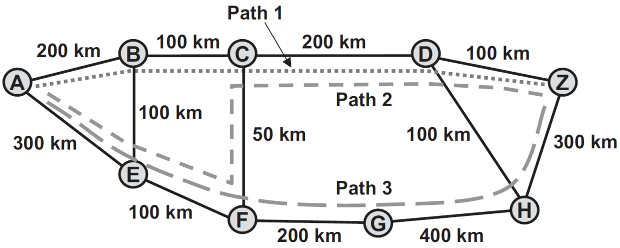


Figure: Links BC, CD, and DZ are assumed to be bottleneck (hot spot) links. Path 1, A-B-C-D-Z, crosses all three of these links. If Link BC is eliminated from the topology, the resulting shortest path, Path 2, A-E-F-C-D-Z, still crosses two of the bottleneck links. All three bottleneck links must be simultaneously eliminated to yield Path 3, A-E-F-G-H-Z. One methodology for estimating hot spot links is to perform a preliminary routing. After identifying the top 10–20 "hot spots" in the network, the next step is to run the shortest-path algorithm, where one bad link or one bad sequence of links is removed from the topology.

Routing Strategies

Fixed-Path

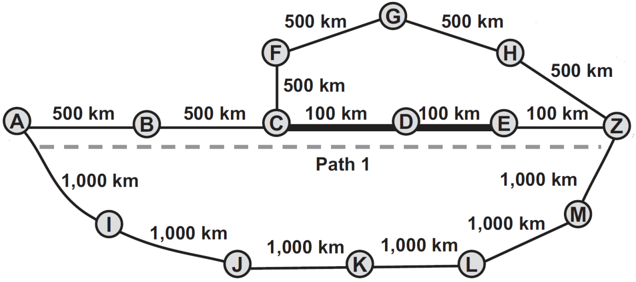


Figure: In fixed-path routing, a path is pre-computed for each source/destination pair. Fixed shortest-path routing may lead to excess blocking and network congestion.

Alternative-Path

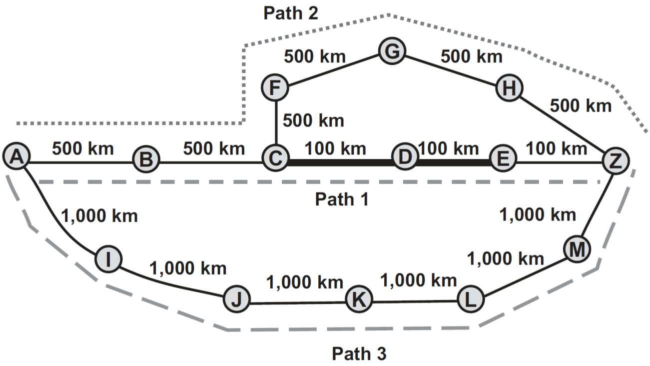


Figure: Two alternative paths between Nodes A and Z are desired for load balancing, with Links CD and DE assumed to be the bottleneck links. With bottleneck diversity, Paths 1 and 2 are selected. If total diversity is required, then Path 3 must be included, which is a significantly longer path. In alternative-path routing, several candidate paths are pre-computed for each source/destination pair. Alternative-path routing results in lower blocking than fixed-path routing. The candidate paths may be forced to be disjoint or may be selected such that the number of hot spot links reduces. A common strategy for selecting a path from the condidtate paths for each demand is to select the feasible path that will leave the network in the "least-loaded" state.

Dynamic-Path

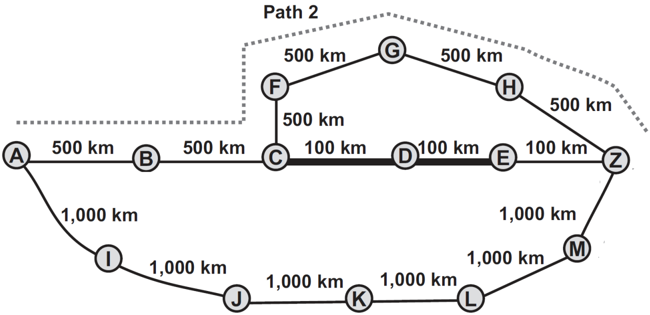


Figure: In dynamic-path routing, the path calculation is performed online at the time of each demand request, based on the current state of the network. The dynamic path selection methodology provides the greatest adaptability to network conditions; however, it is the slowest strategy.

Resource Availability Constraints

O-E-O Network

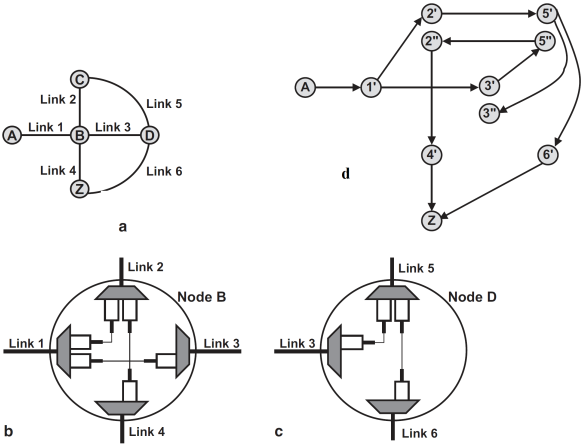


Figure: a Network topology with turn constraints, where a new demand is requested from Node A to Node Z. b The available equipment at Node B. c The available equipment at Node D. d Graph transformation to represent the available equipment in the network. The numbered nodes correspond to the links with the same number, with the prime and double prime representing the two directions of the link.

Optical-bypass Enabled Network

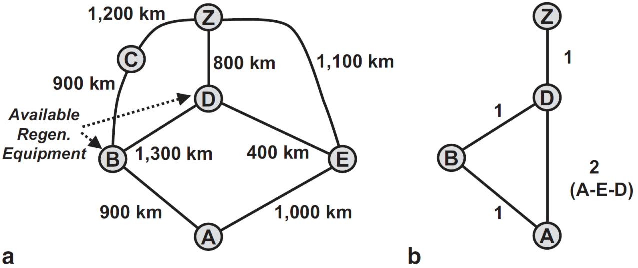


Figure: a Nodes A and Z are assumed to be the endpoints of a new demand request, and Nodes B and D are assumed to be the only nodes with available regeneration equipment. The optical reach is 2,000 km. b The resulting reachability graph.

Diverse Routing

Link and Link+Node Disjoint Paths

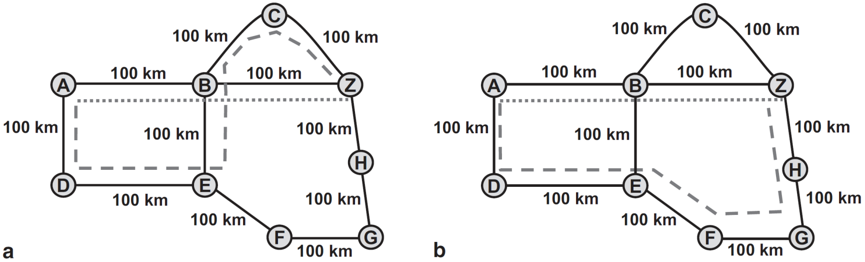


Figure: a The shortest link-disjoint pair of working and protection paths is shown by the dotted and dashed lines. b The shortest link-and-node-disjoint pair of working and protection paths is shown by the dotted and dashed lines.

Shortest Pair of Disjoint Paths

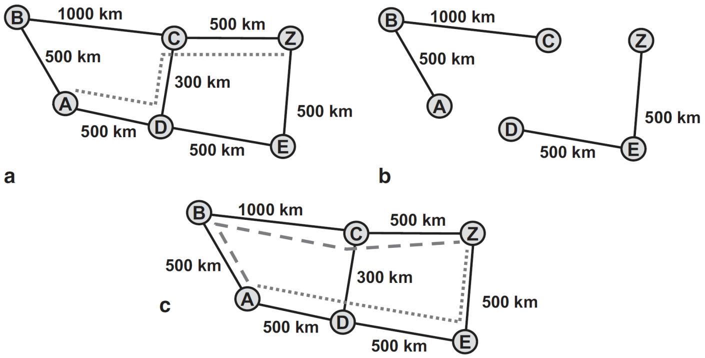


Figure: The shortest pair of disjoint paths, with distance as the metric, is desired between Nodes A and Z. a The first call to the shortest-path algorithm returns the path shown by the dotted line. b The network topology after pruning the links comprising the shortest path. The second call to the shortest-path algorithm fails as no path exists between Nodes A and Z in this pruned topology. c The shortest pair of disjoint paths between Nodes A and Z, shown by the dotted and dashed lines.

Shortest Pair of Disjoint Paths

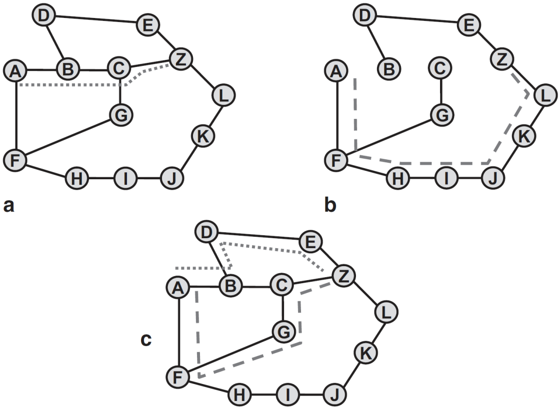


Figure: The shortest pair of disjoint paths, with hops as the metric, is desired between Nodes A and Z. a The first call to the shortest-path algorithm returns the path shown by the dotted line. b The network topology after pruning the links comprising the shortest path. The second call to the shortest-path algorithm finds the path indicated by the dashed line. The total number of hops in the two paths is ten. c The shortest pair of disjoint paths between Nodes A and Z, shown by the dotted and dashed lines; the total number of hops in the two paths is only eight.

Shortest Pair of Disjoint Paths

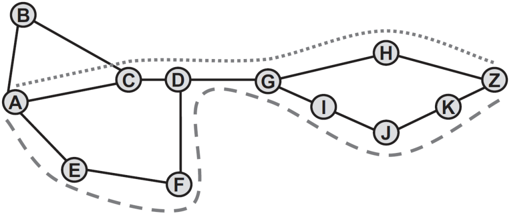


Figure: The two best-known shortest pair of disjoint paths (SPDP) algorithms are Suurballe and Bhandari algorithms. Both algorithms are guaranteed to find the pair of disjoint paths between a source and destination where the sum of the metrics on the two paths is minimized. The SPDP algorithms can be used to find either the shortest pair of link-disjoint paths or the shortest pair of link-and-node-disjoint paths. The SPDP algorithms can be modified to find the shortest maximally link-disjoint (and optionally node-disjoint) paths.

Shortest Pair of Disjoint Paths

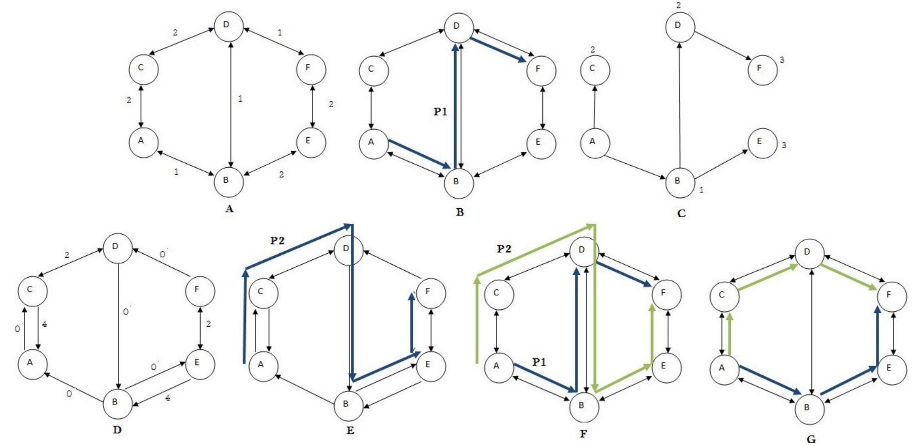
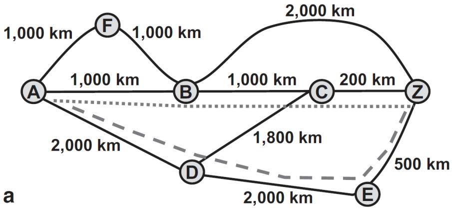


Figure: Suurballe's algorithm to find the shortest pair of link-disjoint paths. A Weighted graph G with distances $w(u, v)$. B Shortest path P1 from A to F. C Shortest path tree with the path length $d(A, u)$. D Residual graph Gt with updated distances $w'(u, v) = w(u, v) - d(A, v) + d(A, u)$ and removed path P1. E Shortest path P2 in the residual graph Gt. F Paths P1 and P2. G Shortest pair of link-disjoint paths with discarded common reversed edges.

Minimum-Regeneration Pair of Disjoint Paths



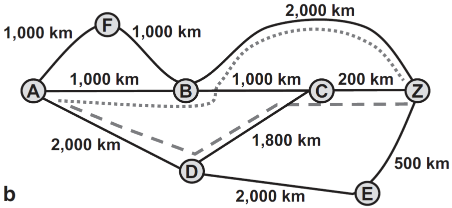


Figure: Assume that the optical reach is 2,000 km. a For a protected connection from Node A to Node Z, the combination of diverse paths A-B-C-Z and A-D-E-Z is the shortest (6,700 km), but requires three regenerations. b The combination of diverse paths A-B-Z and A-D-C-Z is longer (7,000 km), but requires two regenerations. The minimum-regeneration pair of disjoint paths can be found using heuristic algorithms.

Shared Risk Link Groups

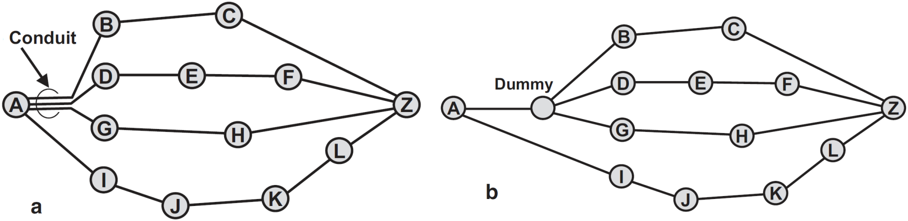


Figure: a In the fiber-level view, Links AB, AD, and AG lie in the same conduit exiting Node A, and thus are not diverse. b Graph transformation to account for the Shared Risk Link Group (SRLG) extending from Node A. A dummy node is added, and each link belonging to the SRLG is modified to have this dummy node as its endpoint instead of Node A. A link is added between Node A and the dummy node, where this link is assigned a metric of zero.

Multicast Routing

Multicast Routing

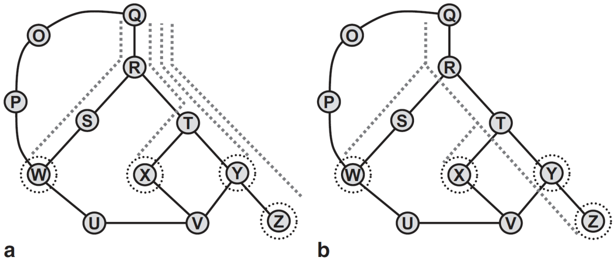


Figure: Four unicast connections are established between the source, Q, and the destinations, W, X, Y, and Z. b One multicast (point to multi-point) connection is established between Node Q and the four destinations. A tree that interconnects the source and all of the destinations is known as a Steiner tree. The weight of the tree is the sum of the metrics of all links that comprise the tree. Finding the Steiner tree of minimum weight is in general a difficult problem and is usually solved heuristically using minimum spanning tree with enhancement (MSTE) and minimum paths (MP).

Minimum Spanning Tree with Enhancement

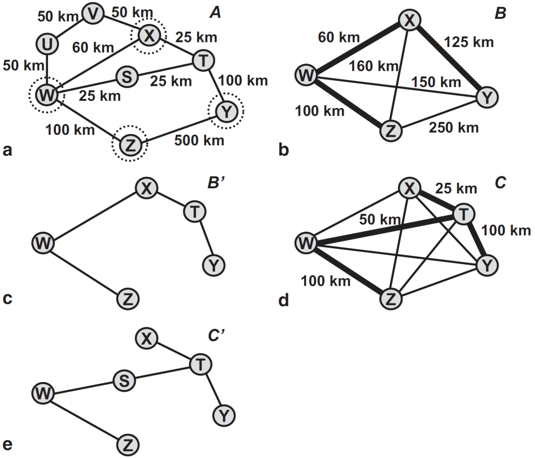


Figure: a Original topology A, where the source and destination nodes are circled. b Topology B formed by interconnecting all source and destination nodes. c The minimum spanning tree on B expanded into paths, forming topology B'. d Topology C formed by interconnecting all nodes of B'. e The minimum spanning tree on C expanded into paths, forming topology C'.

Multipath Routing

Multipath Routing with Differential Delay Constraint

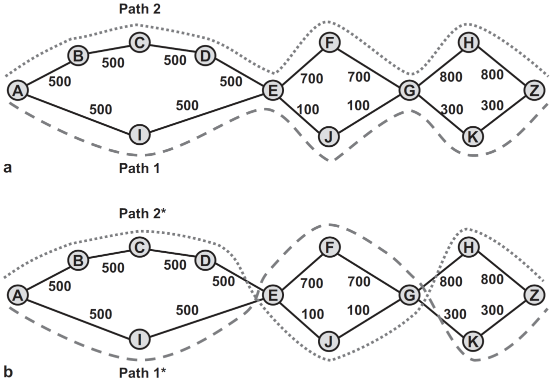


Figure: The process of splitting the aggregate signal into lower-rate signals is known as inverse multiplexing, which is supported in the optical layer by ITU VCAT standard. Here, assume that the maximum allowable differential delay is 5 ms, corresponding to a maximum difference in path distance of $0.005 \times 2 \times 10^5 = 1000$ km. The link labels indicate link distance, in km. a The initial paths have distances of 1,800 km and 5,000 km; the difference, 3,200 km, exceeds the 1,000-km limit. b The subpaths that run between nodes A, E, G, and Z can be swapped to form two new paths of distance 3,000 km and 3,800 km; the difference, 800 km, satisfies the differential delay constraint.

The End