Network Survivability

- Basic concepts
- Classification of survivability schemes
  - Protection, restoration
- SONET ring protection
  - UPSR, BLSR/2, BLSR/4
- Optical ring protection
  - OCh, OMS
  - DP/Ring, SPRing
  - two-fiber, four-fiber
- Optical mesh protection
  - Shared line protection
  - Dedicated path protection
  - Shared path protection
  - SRLG protection

Failures

- Network survivability
  - Ensure that network continues to carry traffic in the event of a failure
- Failure types
  - Fiber cut
  - Dust cut
  - Transceiver failure
  - Node failure
- Failure rates
  - Cable-cut rate: 1-5 cuts/year/1000 km
  - Tx failure rate: 10^8 FIT
  - Rx failure rate: 4311 FIT
  - Failure in Time: average number of failures in 10^9 hours
- Repair Time
  - Equipment MTTR (mean time to repair): 2 hours
  - Cable-cut MTTR: 12 hours
- Example:
  - Cable with 100 strands of fiber
  - Each fiber with 100 wavelengths
  - Each wavelength at 10 Gbps (OC-192)
  - 100 Tbps of data loss
- Other failures
  - Software
  - Lower layer equipment (IP router)

Failure Scenarios

- Single link or node failure
  - At most one failure occurs at a time
- Multiple link or node failure
  - Multiple near-simultaneous failures occur
  - Shared Risk Group (SRG) or Shared-Risk-Link Group (SRLG)
    - Single risk factor affects multiple links or nodes
      - e.g., multiple fibers in a cable or duct

Terminology

- Restoration time
  - Instant that a connection goes down to instant that traffic is restored
- Restoration success rate
  - Ratio between number of successfully restored traffic streams and number of disrupted traffic streams after a failure
- Availability
  - Probability that a system (connection) will be operating and available at some arbitrary time in the future
    - e.g., “five 9s availability” = 99.999%
- Reliability
  - Probability that system (connection) will operate without disruption for predefined period of time

Protection vs Restoration

- Protection
  - Backup resources (routes and wavelengths) pre-computed and reserved in advance
  - Faster recovery time
  - Guaranteed recovery ability
- Restoration
  - When a failure occurs, a backup route and a wavelength are discovered dynamically
  - More resource efficient

Classification - Protection and Restoration
Classification of Protection Schemes

- Protection layer
  - IP (GMPLS), SONET, optical layer (wavelength, waveband, fiber)
- Path vs. line/link
  - Path protection: end-to-end per-channel protection (GMPLS path, SONET circuit, lightpath)
  - Line/link protection: handles all channels on given network link
- Dedicated vs. shared
  - Dedicated:
    - 1 to 1 correspondence between backup resources and working resources
    - Easier management, faster protection switching
    - More resource intensive
  - Shared:
    - Given backup resources are shared by multiple working resources
    - Better resource efficiency
    - Complex management, slower protection switching
- Revertive vs. non-revertive
  - Revertive: when fault is repaired, switch traffic back to primary resources
  - Non-revertive: when fault is repaired, primary resources become backup resources
- Ring vs. mesh

Dedicated Path Protection

- 1+1 protection
  - Each working path has link-disjoint backup path
  - Data transmitted over both paths simultaneously
  - Best signal selected at destination

- 1:1 protection
  - Each working path has link-disjoint backup path
  - Data transmitted only over working path until failure occurs
  - Unused backup path resources may be used for unprotected traffic
  - Requires additional signaling to notify source node

50% of network resources used for protection

Shared Path Protection

- 1:N
  - Protection resources shared by N working paths
  - Reduces resource usage
  - May not be able to handle multiple failures

Link/Line Protection

- Protects all traffic on a failed link
- Handled by the two end nodes of the link
- Routes all traffic around the failed link
- Faster, but less resource efficient than path protection
- Dedicated: 1+1, 1:1
- Shared: 1:N

Span Protection

- Span: Multiple fibers bundled in a conduit.
- Similar to link protection.

Static Protection vs. Dynamic Protection

- Static
  - All connection requests are available
  - Find routing and allocate resources for working and backup paths/links
  - Minimize resource usage
- Dynamic
  - Connection requests arrive one at a time and each connection exists for only a finite duration
  - For each request, find routes and allocate resources for working and backup paths/links
  - Minimize blocking, minimize resource usage
SONET Ring Protection

- Automatic Protection Switching (APS) protocols
- Self-healing rings
- UPSR – Unidirectional Path-Switched Ring
  - 2 fibers
  - Path-based
  - Dedicated 1+1
- BLSR/2 – Bidirectional Line-Switched Ring with 2 fibers
  - Line-based
  - Shared
- BLSR/4 – Bidirectional Line-Switched Ring with 4 fibers
  - Line-based
  - Shared

SONET Layers

- Path – End-to-end connection
- Line – Multiplexing and synchronization
- Section – Regenerator, error monitoring, framing, etc.
- Photonic – Lasers, LEDs, etc.

SONET Layers

- Two Fibers
  - clockwise – working
  - counterclockwise – protection
- Path level protection
- 1+1 dedicated protection
  - 50% network capacity required for protection
  - Bi-directional connection requires 1 unit of bandwidth on all fibers of ring
- Popular for low speed local exchange and access network (OC-3 and OC-12)
  - Simple

SONET BLSR

- Working traffic in both directions
- Line layer protection
- Protection capacities can be shared
  - 50% of network capacity for protection
  - Spatial reuse of bandwidth on ring
- Widely deployed in long-haul and inter-office network
- BLSR/2
  - 2 fibers
  - ½ the capacity of each fiber is reserved for protection
  - Shortest path routing
  - Complex signaling
- BLSR/4
  - 4 fibers
  - One working fiber and one protection fiber in each direction
  - Shortest path routing
  - Span switching on transmitter or receiver failure
  - Ring switching on node failure or fiber cut
  - Most complex signaling
BLSR/2

BLSR/4 Span Switching

BLSR/4 Ring Switching

Optical Layer Protection

- Optical Channel (OCh) Protection
  - Operate on individual light path
  - Path protection
  - Cost may be higher than OMS protection
  - Dedicated: OCh-DPRing
    - Shared: OCh-SPRing
- Optical Multiplex Section (OMS) Protection
  - Operate on all wavelengths in a fiber link
  - Link/span protection
  - Dedicated: OMS-DPRing
    - Shared: OMS-SPRing
- Can use two or four fibers per link

OCh-DPRing

OCh-SPRing

- Similar to SONET UPSR
  - Shared path protection
OMS-DPRing
- Dedicated link protection
- Not very practical
- Each wavelength supports at most one unidirectional lightpath

OMS-SPRing
- Shared link protection
- Similar to SONET BLSR
- On 4 fiber configuration, both span switching and ring switching are supported (for single-fiber failure or entire-link failure)

4-Fiber OMS-SPRing

Mesh Network vs Ring Network
- Why Mesh?
  - More flexible
  - Especially suitable for dense network
  - Require complex management and signaling
- Two Variations:
  - Line/Span Protection
    - Utilize cycles for protection
    - Node cover
    - P-cycle
  - Path Protection
    - Utilize disjoint backup path for protection
    - Dedicated
    - Shared

Static Link/Span Protection
- Minimum Node Cover: One cycle covering all nodes.
- Protect any single link failure
- May have to go through a very long route

Static Link/Span Protection
- Ring Cover: Every link is covered by two cycles (one in each direction)
- For planar graph, one solution is:
  - one cycle on outer face of graph
  - one cycle on each inner face of graph
- May not be resource efficient.
Static Link/Span Protection

- Ring Cover:

Static Link/Span Protection

- P-cycle: Pre-configured cycles
- Extended from ring cover and minimum node cover
- Multiple cycles in the network
- Cycles may protect straddling links
- More resource efficient

Dedicated Path Protection in Single Wavelength Networks

- Two edge or node disjoint paths for each connection
- Requires 50% network capacity for protection
- Static problem
  - Requests known in advance
  - Satisfy all requests while minimizing resource usage
- Dynamic problem
  - Requests arrive one at a time
  - For each request, find route and resources, while minimizing blocking

Static Dedicated Path Protection Problem

- All connection requests are available
- Routing and wavelength assignment problem must be solved for each connection request, both the primary paths and backup paths
- Objective: minimize resources
- NP-hard problem
- Solved by Integer Linear Programming (ILP) or through heuristics

ILP for Static Dedicated Path Protection

- Given: set of connections, physical topology
- Find: set of working and protection lightpaths
- Objective: minimize resources used
- Constraints:
  - For each connection request (s, d), there is exactly one primary path and one protection path exiting s and entering d
  - Primary path and its protection path must be link/node disjoint
  - Flow conservation: Number of paths entering a node must be equal to the ones exiting it.
  - A wavelength on a link can only be used by one primary path or one backup path
  - When a link fails, the number of lightpaths (primary + protection) failed between source-destination pair (s, d) should not exceed the demand between them.

Heuristics for Static Dedicated Path Protection

- Typically consider requests one at a time
- For each request, find primary and backup path
  - Two-step approach: find primary first, then find backup
  - One-step approach: find both primary and backup simultaneously
Alternate Path Algorithm

- Fixed set of possible working paths for each s-d pair
- Fixed set of possible protection paths for each working path
- Choose working path and link disjoint protection path
- Example: W paths in working group, B paths in backup group. Paths within a group are not link disjoint. Paths in different groups are link disjoint.

Simple Two-Step Algorithm

- Run shortest path algorithm to find a working path
- Remove links on working path
- Run shortest path algorithm again to find protection path

Two Step Algorithm

Two Step Algorithm

Simple Two-Step Algorithm

- Problems:
  - The combined cost of the two paths may not be minimal
  - May not find a pair for some topologies – trap topology

Simple Two-Step Algorithm

- One solution: Iterative Simple Two-Step Algorithm
- Take K shortest paths from s to d.
- Run the Two-Step Algorithm for each of the shortest path until certain criterion are met.

Iterative Simple Two-Step Algorithm

- 3 shortest paths from s to d : Red, Blue and Green
- Run Simple Two-Step Algorithm for each of them
Integrated Algorithm – Suurballe’s

- Run shortest path algorithm from s to d
- Set the costs of the links along the shortest path to negative
- Reverse direction of links along the shortest path
- Run shortest path algorithm again
- Remove overlapped links and combine the remaining links
- Minimizes combined cost of working and protection paths
Dedicated Path Protection in Multi-Wavelength Networks

- Now things get a bit more tricky
- Each link has more than one wavelength
- No wavelength converter
- Working path and protection path may be on different wavelengths

Suurballe's algorithm doesn't work.
Simple Two-Step algorithm and Iterative Two-Step algorithm are OK but do not give the best results.
It is a NP-complete problem!
Numerous heuristics exist. The Simple Two-Step is one of them.

Dedicated Path Protection in Networks with Shared-Risk Link Groups (SRLGs)

- Another variation of tricky networks
- Single wavelength or multi-wavelength with wavelength converters
- Multiple links may fail simultaneously
  - Examples:
    - Lightpaths routed over same physical fiber
    - Lightpaths routed over different fibers but all the fibers are bundled or routed over same terrain
- Shared-Risk Link Group: Set of physical or logical links that are affected by the same failure event

Solutions exist for special topologies
NP-Complete if risks are randomly distributed in the network
One heuristic solution:
- Run Suurballe’s algorithm first
- Run Simple Two-Step Algorithm for each of the two paths under the SRLG disjoint constraint
- Pick the pair with the minimal combined cost

Static Shared Path Protection Problem

- All connection requests are available.
- Routing and wavelength assignment problem must be solved for each connection request, both the primary paths and backup paths
- Two primary paths may share resources on their backup paths as long as the primary paths are link disjoint
- NP-complete problem
- Solved by Integer Linear Programming (ILP) or through heuristics

ILP for Static Shared Path Protection

- Given: set of connections, physical topology
- Find: set of working and protection lightpaths
- Objective: minimize resources used
- Constraints:
  - Applicable primary protection constraints
  - Two lightpaths protected by the same wavelength w on the same link cannot go through the same link
  - Wavelength w on link i->j can only be utilized by either a primary path or by protection paths
  - A primary path should not have more than one protection path
Dynamic Shared Path Protection

- More bandwidth efficient
- More complex than dedicated protection
- Additional shared protection constraints:
  - The number of shared protection paths on one wavelength of a link can not exceed the maximum.
  - Two working paths that have common SRLGs can not share protection paths.
- Set up working and protection paths to maximize shared capacity: Set the cost of the links on existing protection path to zero.

Shared Path Protection Heuristics

- **Centralized**
  - Central controller maintains for each wavelength on each link:
    - Available
    - Reserved for working path
    - Reserved for protection path
    - Set of working paths that use this wavelength on this link for protection
- **Distributed with full information**
  - Each node maintains information as in centralized case:
    - Information distributed to nodes via flooding (e.g., OSPF)
- **Distributed with limited information**
  - Each node maintains for each wavelength on each link:
    - Available
    - Reserved
    - Each node maintains for each wavelength on its own links:
      - Available
      - Reserved for working path
      - Reserved for protection path
      - Set of working paths that use this wavelength on this link for protection
    - Route calculation done by source node
    - Sharing and wavelength assignment decisions for protection path made on a hop-by-hop basis

Other Protection Problems

- Shared protection with SRLG constraint
- Minimum-risk path problems
- Maximum survivability problems