Designing VNT Candidates Robust Against Congestion Due to Node Failures

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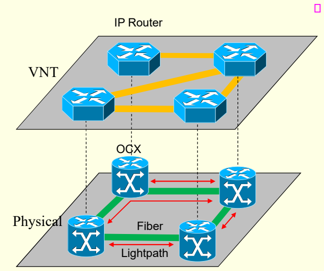
Outline

- Problem Statement
- Objective
- Proposed Algorithm
- Analytical Model
- Simulation Results
- Conclusions
- Future Research

Problem Statement

- **The global Internet traffic is growing at a tremendous rate.**
- **Compared to electrical cabling, optical fiber with wavelength division multiplexing (WDM) allows much higher bandwidth and can span longer distances**
- **However, due to the difficulties of high granularity switching at ultra high speed of optical networks, the processing and switching at optical nodes have important limitations.**
- **An optical fiber may carry hundreds of wavelengths, but it is difficult to terminate each wavelength at each node due to limited number of transmitters and receivers in nodes.**
- **A common solution for these problems is constructing a logical virtual network topology (VNT) on a physical topology.**

Problem Statement (2)



- **Virtual Network Topology**
  - VNT is a logical topology, where only the physical nodes, which are the transmitter and receiver edges of a lightpath, are shown as connected by a link.
  - Modifying the VNT by changing the placement of lightpaths between nodes allows adapting the network for changing traffic conditions and new application layer services.

Problem Statement (3)

- **Works in the literature on VNT configuration may be classified into two groups as online and offline approaches**
- **Offline approaches create VNTs suitable for a limited set of possible traffic demand matrices.**
  - However Internet traffic is difficult predict as new applications and services, which can dramatically change the traffic, appear in time.
  - Moreover, it is difficult to predict the traffic changes due to node/link failures, cyber attacks etc.
- **Online approaches sample the traffic demand periodically and design a new VNT for the current environment.**
  - However, they require up-to-date traffic demand matrix information, which can be challenging to retrieve.
  - Some of them cannot handle traffic changes due to node or link failures and some of them need to know detailed information like exact place of failures

Objective

- **Failures in the physical topology are common due to a system failures, natural disasters or cyber attacks like denial-of-service (DoS)**
- **Both online and offline approaches have limitations and problems when recovering from a large scale failure**
- **Our objective is to design VNT candidates,**
  - which can accommodate a wider range of traffic patterns compared to a random VNT by minimizing the maximum lightpath load in the network, without requiring the traffic matrix
  - which can prevent congestion with a high probability right after a failure.
  - We propose two heuristic algorithms to design VNT candidates
- **However, a single VNT candidate may not be able to give low utilization after each change in traffic pattern or each change in topology after a failure.**
  - We also present an attractor selection mechanism, which is similar to the system used by living organisms, in order to recover from difficult topology failures.

Designing VNT Candidates

- We propose two heuristic algorithms for designing VNT candidates called MFLDA (Minimum Flow Logical topology Design Algorithm) and MFLDA-FO (MFLDA with Failure Optimization)
  - Both algorithms design VNT candidates, which can accommodate a wide range of traffic patterns.
  - The VNT candidates designed by MFLDA-FO have also lower probability of congestion even after changes in the physical topology due to failure of multiple nodes.
- The design philosophy:
  - The probability of a congestion on a lightpath increases with the increasing number of source-destination nodes pairs using the lightpath along their route.
  - Minimize the number of source-destination node pairs on the lightpaths.

Implementation

- Both algorithms start from a seed logical topology and incrementally establish new lightpaths.
- Each time a new a lightpath is established, the algorithm collects data on the current logical topology in order to select the next node pair where establishing a lightpath can minimize the congestion probability.
  - MFLDA collects data only on the current logical topology after establishing a new lightpath
  - Besides the current topology, MFLDA-FO also simulates single node failures in the physical topology and collects data on the failed topologies, which allows the created VNT to be more robust against the failures at these nodes
- Based on the collected data, the algorithms establish a lightpath between a node pair, which can minimize the congestion probability in the logical topology

Attractor Selection Algorithm

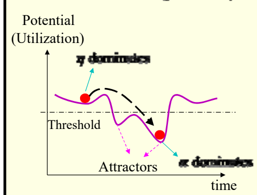
- Living organisms are well-known to adapt to the changes in the environment.
- It is shown that an attractor selection mechanism is adopted to adapt to the environment and recover in order to increase the probability of survival.
- Applying attractor selection mechanism to optical networks allows solving complex failure scenarios, which cannot be solved by VNT optimization alone.

Analytical Model of Attractor Selection

- The VNT is controlled by the equation:

$$\frac{dx_i}{dt} = \alpha \cdot f(x_1, \ldots, x_n) + \eta$$

  - Each lightpath is controlled by a gene, so i^{th} lightpath has an expression level of x_i
  - α is the growth rate, which is calculated according the maximum utilization level in the IP network as a feedback.
  - The η is the Gaussian noise term showing the strength of stochastic behavior
  - The rate of change in the expression level by the deterministic behavior is given by $f(x)$

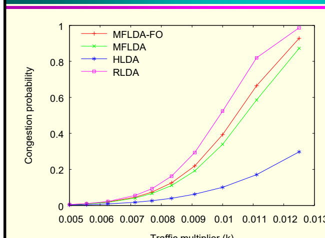


- The system state fluctuates due to noise η
- Attractors are stable local minimum potential points. The system moves towards the attractors.
- When the maximum utilization level is high, α decreases, so η dominates the equation, which causes the VNT to change randomly to find a new attractor.
- When the system condition is good (low potential due to low utilization), α dominates, so the system converges to the attractor and stabilizes
- When the system conditions get worse, α decreases and the system finds a new attractor and the system recovers

Simulation Parameters

- Simulated Waxman physical topology with 100 nodes and 400 optical fibers, one fiber for each direction
- The number of lightpath transmitters and receivers is limited to 16
- Each VNT candidate set was tested with 500.000 traffic matrices
- A VNT is marked as congested if its maximum wavelength utilization is over 0.5 (50%)
- When a node fails, the lightpaths passing through its links fail at the same time. They are not established again.
- Shortest path routing is applied

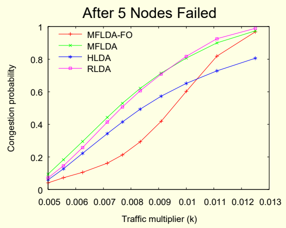
Congestion Probability without Node Failures

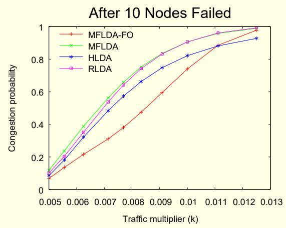


- MFLDA: The proposed algorithm without optimization for node failures
- MFLDA-FO: The proposed algorithm with optimization for node failures
- HLDA: Heuristic Logical topology Design Algorithm establishing lightpaths among the s-d pairs with the highest traffic according to the traffic matrix.
- RLDA: Random Logical Topology Design Algorithm establishing lightpaths among randomly chosen node pairs

- HLDA gave the lowest probability of congestion. As HLDA has the traffic matrix information and it designs a specific VNT for each traffic matrix, this is an expected result. However, our aim is to design VNT candidates without traffic matrix information.
- RLDA gave the highest congestion probability.
- MFLDA gave lower congestion probability than MFLDA-FO. The reason is that the failure optimization causes the VNT to include extra backup paths against possible failure scenarios.

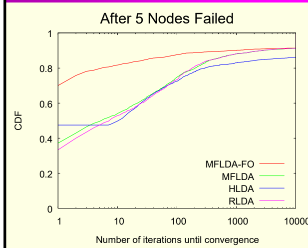
Congestion Probability after Node Failures





- **MFLDA-FO gave the lowest congestion probability unless the traffic was too high.**
- **While HLDA had both the traffic matrix and failed node list information, it could not create direct lightpaths among some of the s-d pairs with high traffic, which pass through failed nodes. They may end up using multiple lightpaths and concentrate on some lightpaths and cause congestion.**
- **MFLDA-FO optimizes the VNT by taking failures into account to prevent hot-spots, so it gave lower congestion probability unless the traffic was too high.**

Convergence with Attractor Selection



- **The attractors designed our MFLDA-FO gave much faster convergence than both RLDA and HLDA algorithms**
- **While MFLDA-FO had lower probability of congestion than other algorithms right after failure, not all possible failure scenarios could be solved by VNT optimization alone.**
- **Attractor selection mechanism allows solving complex failure scenarios after some iterations.**
- **Cumulative distribution function (CDF) of the number of iterations by attractor selection algorithm until it finds a VNT, which has maximum lightpath utilization less than 50%.**
- **The VNT candidates were set as the attractors of the attractor selection algorithms.**
- **Five randomly chosen nodes failed before the first iteration.**

Conclusions

- **Proposed an algorithm called MFLDA for designing VNTs, which can accommodate wider range of traffic patterns without traffic matric information.**
- **Presented an extended version called MFLDA-FO to design VNTs robust against congestion due the traffic and topology changes after network failures.**
- **MFLDA-FO can accommodate a wider range of traffic both before and right after a failure of multiple nodes.**
- **As not all possible failure scenarios could be solved by applying a single optimized VNT, an attractor selection control mechanism was applied.**
- **The converge time is faster when VNTs designed by MFLDA-FO are used in the attractor selection algorithm**
- **Unlike HLDA, our VNT design algorithms and the attractor selection algorithms do not require traffic matrix information and failed node list.**

Future Work

- **While it is easy to estimate the data based on routing stats used by our heuristic algorithm when shortest path routing is applied, it may take time with some routing algorithms.**
- **As a future work, we will investigate the possible implementation issues with other routing algorithms and evaluate their performance.**

Thank you