Optimization of Routing and Resource Allocation in Communication Networks

HDR Defence Presented by

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Prof. Nathalie Mitton	INRIA, Lille	Examiner
Prof. Abderrezak Rachedi	LIGM, University of Marne-la-Vallée	Examiner

Avignon, Sept. 26th, 2018

Outline

Curriculum Vitae

- 2004 - 2007 Master on Telecommunications
  Northwestern Polytechnic University, China
- 2007 - 2010 PhD on Optical Networking
  IRISA, INSA of Rennes, France
- 2010 - 2012 Post-doc on Content Delivery Networks
  IMT Atlantique (ex Télécom Bretagne)
- 09/2012 - 09/2018 Associate Professor on Networking
  LIA lab, CERI
  University of Avignon
- 09/2018 - present Associate Professor on Networking
  LISITE lab
  Institut Supérieur d'électronique de Paris (ISEP)

Resume

Responsibilities + Awards

- Awards: PEDR 2016-2020; IEEE senior member, etc
- Responsibles: Master RISM; axis FR Agorantic
- Conference organisations: ICNC, WCSP, Wimob, Netgcoop, MoWnet
- Project coordinations: 5 Eiffel+CSC scholarships, regional projet, Sino-French project...

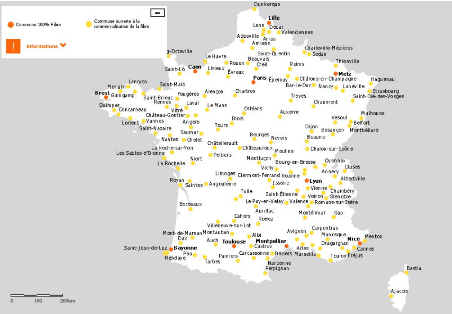
Research

- Routing, resource allocation, survivability and security in networking
- Routing optimization in ITS
- Advising: PhD (10), interns (6)
- Publications: journals (25), conferences (44)

Teaching

- 1600h, 3rd year engineer, L2/L3/M1/M2
- Networking, multimedia, CISCO, graph theory

Communication Networks



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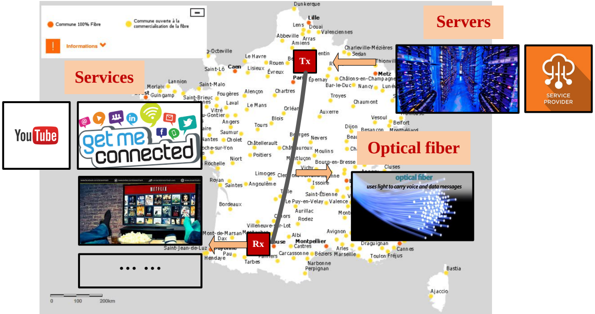
Communication Networks



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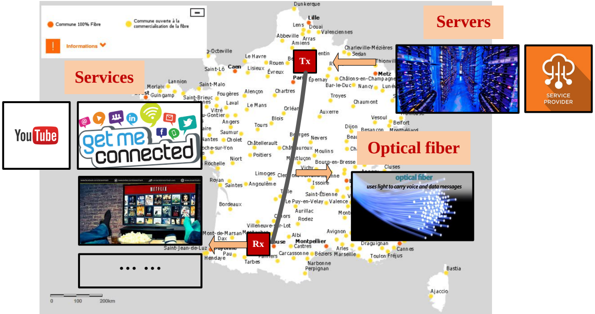
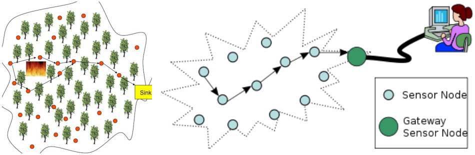
Communication Networks





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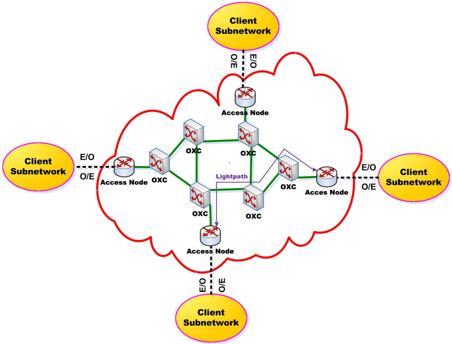
Studied Problem in Communication Networks

Routing and Resource Allocation

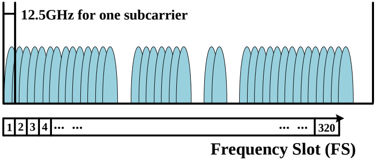
- Routing: path, tree, etc.

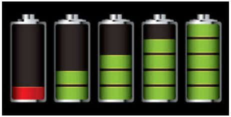


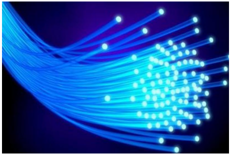
Studied Problem in Communication Networks

Routing and Resource Allocation (RRA)

- Routing
- Resource allocation: spectrum, battery, bandwidth, capacity etc.







Optimization of Routing and Resource Allocation

Challenges

- Coupled together
- NP-Hard problems
- Optimization techniques required

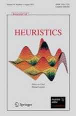
Optimization techniques

Integer Linear Programming

- Optimal solution
- High computation complexity

Heuristics and Approximation Algorithms

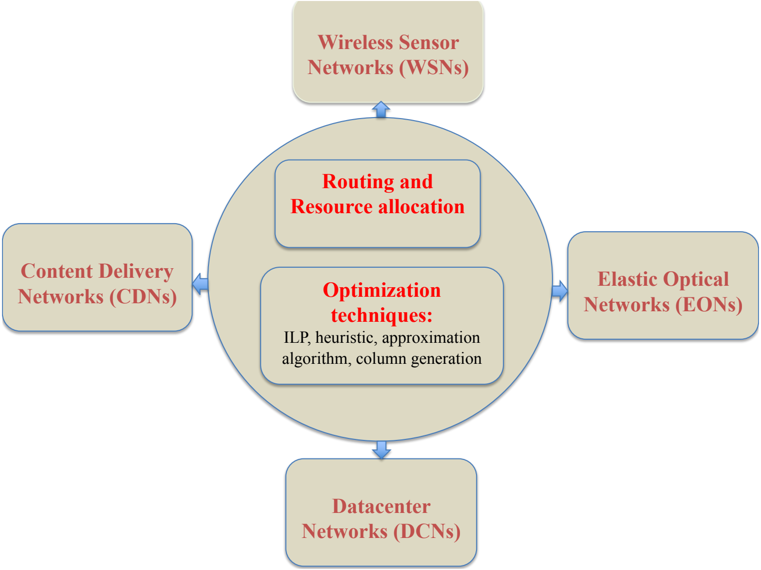
- Feasible solution, approximation ratio
- Low computation complexity



Large-scale optimization: Column Generation

- Near-optimal solution
- Relatively low computation complexity

RRA in Communication Networks



Motivation

- OTT content providers: twitch, ustream, second screen video...
- User-generated live video traffic: exploding
- Telco-CDN: tight resource and deployment constraint

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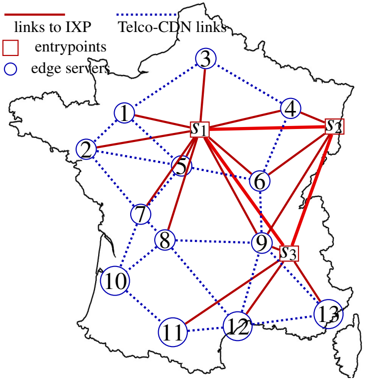
- OTT content providers: twitch, ustream, second screen video...
- User-generated live video traffic: exploding
- Telco-CDN: tight resource and deployment constraint
- Problem: How to manage live video traffic? (CNG projet, thesis of Jiayi Liu)



Multi-channel video delivery problem

Description

- Teleco-CDNs $G(V,E)$, entrypoints $s_i \in S \subset V$
- Video channels $i \in \mathcal{I}$, channel importance π_i
- Deliver channel $i \in \mathcal{I}$ from s_i to subscribing edge-servers $V_i \subset V$ with rateless coding
- Multi-tree overlay F_i: one distinct unit of rateless codes per tree

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Constraints

- **Edge-server capacity constraint** (c_v).

$$\sum_{i \in \mathcal{I}} \sum_{T \in F_i} deg_T^+(v) \leq c_v, \forall v \in V \tag{1}$$

- **Rateless codes constraint** $\hat{K}$.

$$\forall i \in \mathcal{I}, \forall v \in V_i, |F_i(v)| \geq \hat{K} \tag{2}$$

- **QoS (delay) constraint** H.

$$\forall i \in \mathcal{I}, \forall T \in F_i, \forall v \in T, \quad \sum d_e \leq H \tag{3}$$

Multi-channel video delivery problem

Objectives

- Main: Max overall importance of the delivered video channels, *i.e.*, $\sum_{i \in \mathcal{I}} R_i \times \pi_i$
- 2nd: Min traffic load, *i.e.*, number of links in the overlay

Multi-channel video delivery problem

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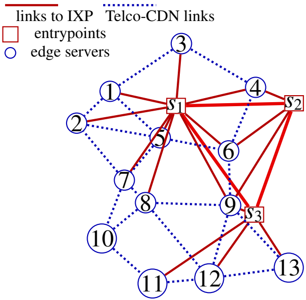
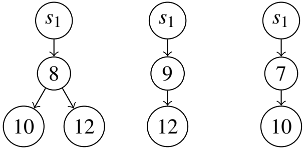
Telco-CDN



Example of a multi-tree overlay

Entrypoint s_1; subscribing edge-servers: 10 and 12, delay $H = 2$, and rateless codes parameter $\hat{K} = 2$, upload capacity $c_8 = 2$



Proposed Solutions

Problem Decomposition

- Overlay construction: capacity-and-delay-bounded min-cost forest
- Bandwidth allocation: multi-dimension knapsack

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ILP formulations

- SOP-ILPs: ILP-Overlay + ILP-Bandwidth $\rightarrow$ Suboptimal.
  c_v^i: capacity reserved by edge server $v \in V$ for forest F_i:

$$\sum_{i \in \mathcal{I}} c_v^i \times R_i \leq c_v, \qquad \forall v \tag{4}$$

Proposed Solutions

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$$\sum_{i \in \mathcal{I}} c_v^i \times R_i \leq c_v, \qquad \forall v \tag{4}$$

- JOP-ILP (overlay construction + bandwidth allocation) $\rightarrow$ Optimal.
  $L_{uv}^{ik} \in \{0, 1\}$: Is 1 if arc (u, v) is used in T^{ik}, 0 otherwise.

$$\sum_{i \in \mathcal{I}} \sum_{k \in \{1, \ldots, W_i\}} \sum_{u \in N^+(v)} L_{vu}^{ik} \leq c_v, \qquad \forall v \tag{5}$$

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Heuristics

- SOP1-heu: two-step optimization
  Heu-Overlay for all first, then Heu1-Bandwidth (sorting π_i)

Proposed Solutions

Problem Decomposition

- Delivery Overlay: capacity-and-delay-bounded min-cost forest
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Heuristics

- SOP1-heu: two-step optimization
  Heu-Overlay for all first, then Heu1-Bandwidth (sorting π_i)
- SOP2-heu: two-step optimization
  Heu-Overlay for all first, then Heu2-Bandwidth (knapsack and bin packing)

Proposed Solutions

Problem Decomposition

- Delivery Overlay: capacity-and-delay-bounded min-cost forest
- Bandwidth allocation: multi-dimension knapsack

Heuristics

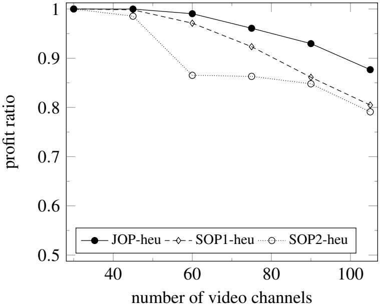
- SOP1-heu: two-step optimization
  Heu-Overlay for all first, then Heu1-Bandwidth (sorting π_i)
- SOP2-heu: two-step optimization
  Heu-Overlay for all first, then Heu2-Bandwidth (knapsack and bin packing)
- JOP-heu: Divide and Conquer
  Recursive overlay construction + Bandwidth allocation:

Heuristic vs. Optimal

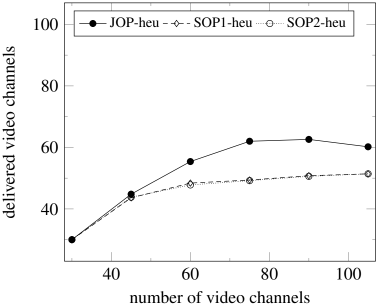
Table 1: Heuristic Solutions vs MILP Solutions: 6 channels

video bit-rate	*JOP-ILP*	*SOP-ILP*	*JOP-heu*	*SOP1-heu*	*SOP2-heu*
Profit ratio					
512 kbps	100%	100%	100%	100%	100%
1024 kbps	100%	90.7%	100%	100%	100%
1536 kbps	100%	76.7%	100%	100%	100%
2048 kbps	100%	67.4%	100%	93%	76.7%
Number of delivered channels					
512 kbps	6	6	6	6	6
1024 kbps	6	4.5	6	6	6
1536 kbps	6	3.5	6	6	6
2048 kbps	6	3.5	6	5	5
Ratio of used capacity					
512 kbps	12.7%	12.8%	14%	13.8%	13.8%
1024 kbps	21.7%	16.5%	23.7%	23.3%	23.3%
1536 kbps	30.8%	18.1%	33.2%	32.7%	32.7%
2048 kbps	40.4%	21.2%	42.6%	36%	34.3%
Average computing time (Seconds)					
2048 kbps	749.5	228	0.3	< 0.1	0.3

Results of Heuristics in French CDN - 1



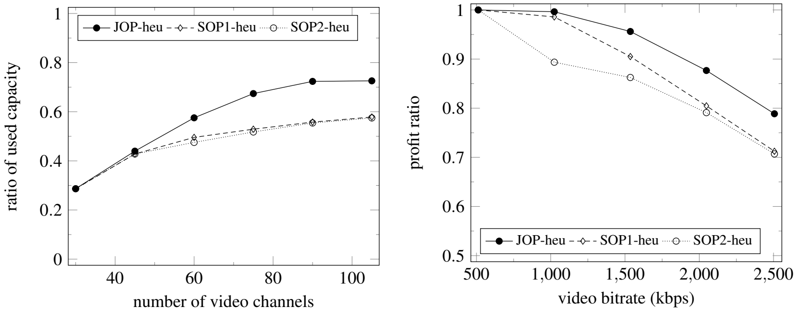
(a) profit ratio vs. channels



(b) delivered channels vs. channels

Figure 2: Simulation Results in a French Telco-CDN

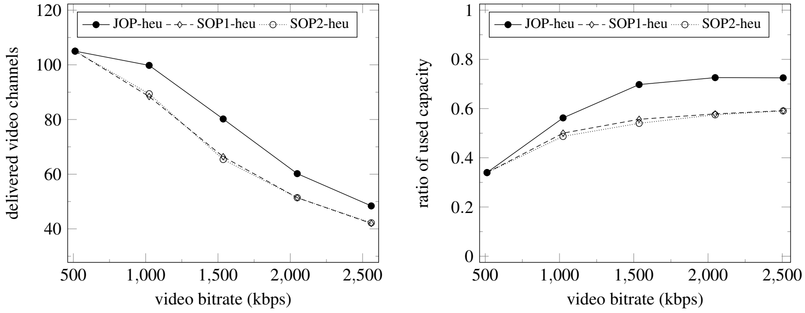
Results of Heuristic in French CDN - 2



(a) capacity ratio vs. channels (b) profit ratio vs. bit-rate

Figure 3: Simulation Results-2 in a French Telco-CDN

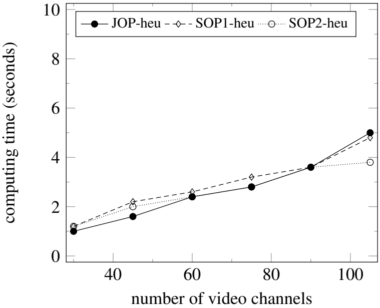
Results of Heuristics in French CDN - 3



(a) delivered channels vs. bit-rate (b) capacity ratio vs. bit-rate

Figure 4: Simulation Results in a French Telco-CDN

Computation Time of Heuristic



(a) Computing time in French-CDN (16 nodes)

Figure 5: Average Computing Time (seconds) on Real-Scale Systems: 30 ∼ 105 channels, video bitrate 2048 kbps

Summary of Video Delivery in Telco-CDNs

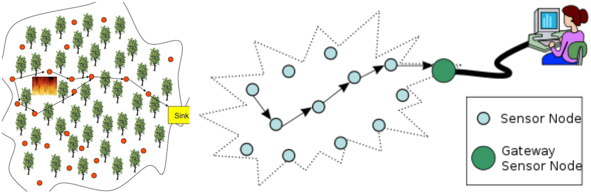
Joint optimization of Video Delivery

- Delivery of multiple video channels in Telco-CDNs
- Joint optimization vs. two-step optimization
- JOP serves 1/3 more channels, and also time-efficient

Wireless Sensor Networks (WSNs)

Applications

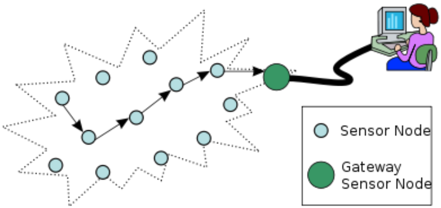
- Environment monitoring: forest, pollution etc.
- Health monitoring
- Habitat monitoring



Data Collection and Transmission

Data Gathering Tree

- Data collection in each time slot
- Data transmission: many-to-one communications
- Tree optimization: maximize lifetime



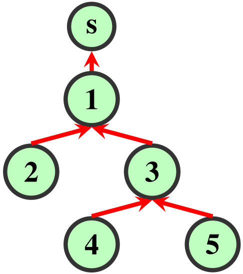


Figure 6: An example of a data-gathering tree

Motivations

Literature

- Only *heuristic algorithms* are proposed
- Only *simple energy consumption model* is considered
- *Exact solution* is missing except exhaustive search
- Either *routing* or *data aggregation* is proposed for improving network lifetime

This work

- Three data aggregation techniques
- Exact solution using MILP formulations
- Joint optimal routing and data aggregation
- Gain on network lifetime

Maximum-Lifetime Data-Gathering Tree

Data Gathering Tree

- Static sensor nodes: wireless + limited battery
- Single sink: sensors report data to the sink in each time slot
- Data aggregations
- Data collection tree
- Maximize network lifetime of tree (the number of time slots)

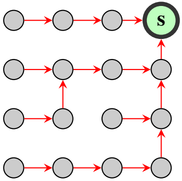


Figure 7: Data collection using a WSN

Maximum-Lifetime Data-Gathering Tree

Sensor Lifetime (number of time slots)

- Emission energy unit e^t /packet
- Reception energy unit e^r/packet
- Computing equation

$$L_v^T = \frac{E_v}{n_v^t \cdot e^t + n_v^r \cdot e^r} \tag{6}$$

Network Lifetime (number of time slots)

- The time duration until the first sensor node is out of battery, i.e., $L = \min_{v \in V}\{L_v^T\}$
- Critical for full monitoring in WSNs

Data Aggregation Techniques

Aggregation Modes

- Full Aggregation Mode (FAM)
- No Aggregation Mode (NAM)
- Hybrid-Aggregation Mode (HAM) using Compressive Sensing

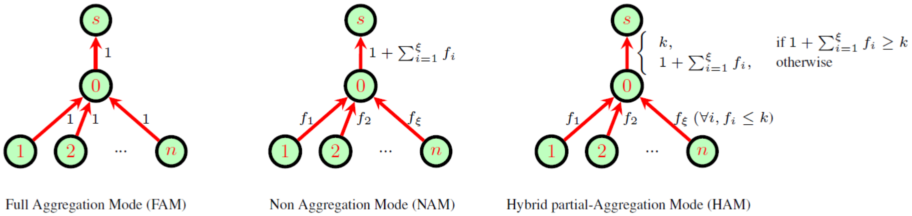


Figure 8: Comparison of different data compression methods

Energy Consumption Model

Sensor Lifetime

$$L_v^T = \frac{E_v}{n_v^t \cdot e^t + n_v^r \cdot e^r} \quad (7)$$

Full Aggregation Mode (FAM)

- Statistical queries: sum, max, ...

$$L_v^T = \frac{E_v}{e^t + d_v^T \cdot e^r} \quad (8)$$

d_v^T is the number of incoming links of sensor v in tree T. In Fig. 9, $d_1^T = 2$ for node 1 in FAM

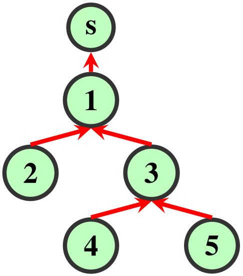


Figure 9: A data-gathering tree

Energy Consumption Model

Sensor Lifetime

$$L_v^T = \frac{E_v}{n_v^t \cdot e^t + n_v^r \cdot e^r} \tag{9}$$

No Aggregation Mode (NAM)

- No compression: Pictures, air parameters for different regions, etc

$$L_v^T = \frac{E_v}{e^t + f_v^T \cdot (e^t + e^r)} \tag{10}$$

f_v^T denotes the number of sensors using v as a relay to report data to s (including all descendants of sensor v). In Fig. 10, $f_1^T = 4$ for node 1 in NAM

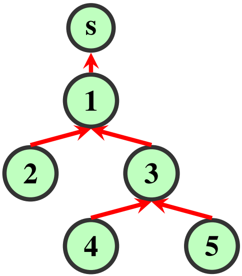


Figure 10: A data-gathering tree

Energy Consumption Model

Sensor Lifetime

$$L_v^T = \frac{E_v}{n_v^t \cdot e^t + n_v^r \cdot e^r} \tag{11}$$

Hybrid-Aggregation Mode (HAM)

- Compressive Sensing (partial compression): ocean data

$$L_v^T = \frac{E_v}{\min\{\hat{f}_v^T + 1, k\} \cdot e^t + \hat{f}_v^T \cdot e^r} \tag{12}$$

Let $\hat{f}_v^T$ be the number of data units received from the incoming links of sensor v. In Fig. 11, if $k = 4$, then $\hat{f}_1^T = 4$ for node 1.

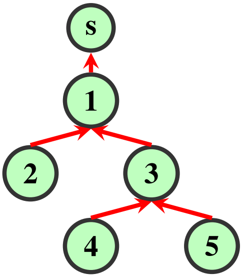


Figure 11: A data-gathering tree

Problem: Maximum-Lifetime Data-Gathering Tree

Given parameters

- WSN topology $G(V, E)$ and wireless transmission range
- e^t and e^r
- Data aggregation modes (FAM, NAM, HAM)
- Energy consumption model

Objective

- Find a data collection tree from sensors to the sink
- Maximize network lifetime: $\max L$

Problem: Maximum-Lifetime Data-Gathering Tree

Challenges

- **NP-Hard**
- Different aggregation modes
- Non-linear relationship between lifetime and the number of transmitted and received messages in Eq. (13)

$$L_v^T = \frac{E_v}{n_v^t \cdot e^t + n_v^r \cdot e^r} \tag{13}$$

- Maximizing network lifetime (gathering tree)
- Three MILP formulations

Simulation Configurations

Parameters and Tools

- Initial energy 1 J
- Emitting energy e^t=6.4 μJ
- Receiving energy e^t=12.8 μJ
- 100×100 m^2 grid with an interval of 10 m
- C++ and IBM ILOG CPLEX 12.2

Evaluations

- Network lifetime vs. Number of sensors
- Network lifetime vs. Transmission range
- Network lifetime vs. Compression factor k

Topologies

- Sensors on the grid ($100 \times 100\ m^2$)
- Configuration I: Sink in the center
- Configuration II: Sink at a corner

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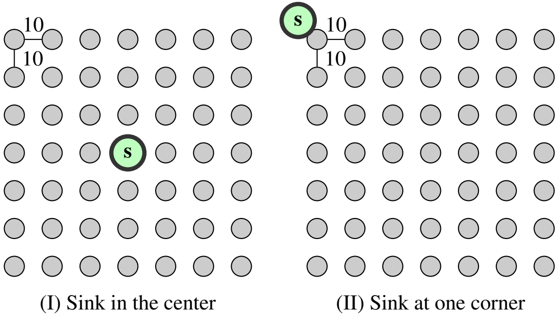
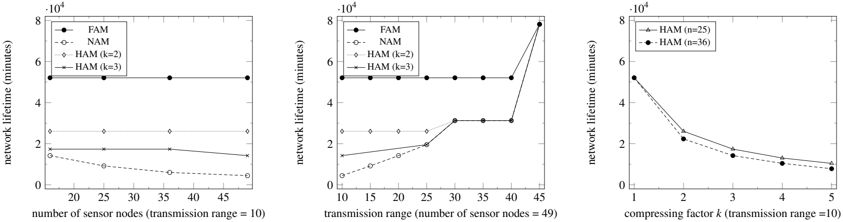


Figure 12: WSN grid topology with different sink positions

Numerical Results

Results for Configuration I



(a) Lifetime vs. # Sensors (b) Lifetime vs. Range (c) Lifetime vs. k

Figure 13: Simulation Results for Configuration I (sink at the center)

Data Accuracy vs. k

Table 2: Performance Evaluation of HAM (25 sensors, and sink node in center)

Metrics	$k = 1$	$k = 2$	$k = 3$	$k = 4$	$k = 5$
Lifetime	52083	26041	17361	13020	10416
Maximum Delay	10	10	10	8	6
Data Accuracy	25%	36%	52%	72%	80%

Summary of Data Collection

- Data gathering tree with maximum network lifetime
- Joint routing and data aggregation
- Three MILP formulations
- Network Lifetime increases fivefold
- Tradeoff between data accuracy and network lifetime

Motivations

Elastic Optical Networks (EONs)

- Huge bandwidth
- Low latency
- Spectrum flexibility

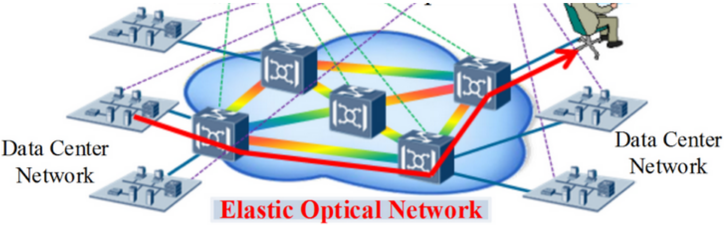


Figure 14: EONs

Motivations

Spectrum resource in optical fibers

- Narrow-band (12.5GHz or less) frequencies → Frequency Slots (FS')
- Flexibility
- Limited number of FSs

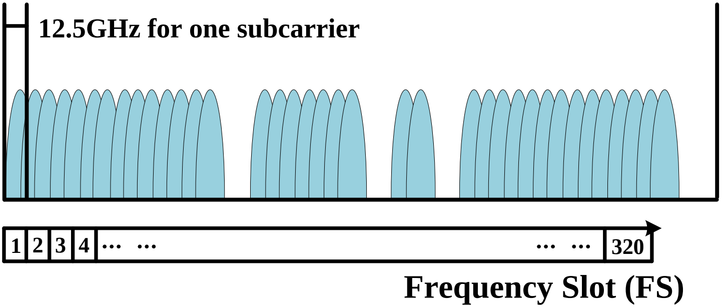
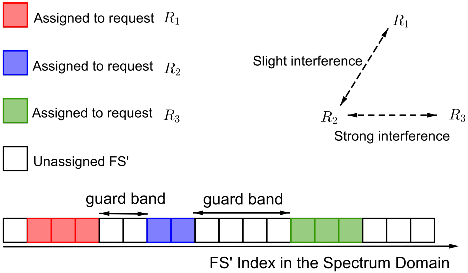


Figure 15: EONs and FS

Distance Spectrum Allocation (DSA) in EONs

Guard Band (GB)

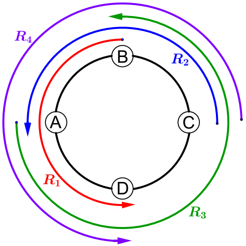
- Two requests (lightpaths) with common links
- Interference Mitigation for QoT
- Physical layer security
- Heterogeneous GB size $\rightarrow$ Spectrum efficiency

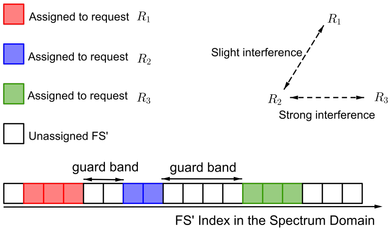


Distance Spectrum Allocation (Thesis of Haitao Wu)

Spectrum Conflicts

- Inside a lightpath: Spectrum continuity
- Inside a lightpath: Spectrum contiguity
- Between lightpaths: Guard Band (GB) separation





Conflict Graph $G(V, E)$

- $v \in V$: Vertices set with each node representing a request (lightpath)
- $e = (v_i, v_j) \in E$: (v_i, v_j) exists if lightpaths v_i and v_j share common links
- $s \in \mathbb{N}^+$: Index of an FS
- $v \in V$: Vertices set with each node representing a request (lightpath)
- v_i^w: Number of FSs required by request i
- w_{v_i}: Set of contiguous FSs assigent for request i
- v_i^b, v_i^a: Begin/end index of FS assigned for request i
- d_e: Least guard band size for separating lightpaths v_i and v_j

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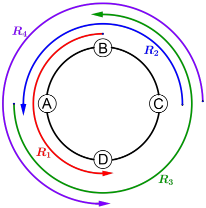
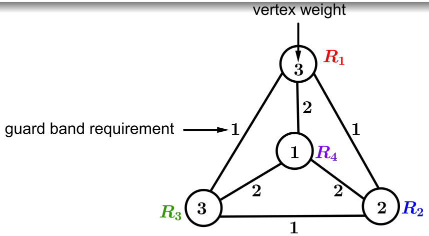
Request	Bandwidth
R_1	3 FS'
R_2	2 FS'
R_3	3 FS'
R_4	1 FS'





DSA Model

Objective: Minimize the maximum FS index assigned

$$\text{Minimize} \quad \max_{s \in \left(\bigcup_{v_i \in V} w_{v_i} \right)} (s) \qquad (\mathbf{DSA}), \qquad (14)$$

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Constraints

- Bandwidth Requirement Constraint

$$|w_{v_i}| = v_i^w, \ \forall v_i \in V, \tag{15}$$

- Spectrum Continuity Constraint: satisfied automatically
- Spectrum Contiguity Constraint: $w_{v_i} = \{v_i^b, v_i^b + 1, ..., v_i^a - 1, v_i^a\}$
- Spectrum Distance Constraint

$$\text{distance}(w_{v_i}, w_{v_j}) \geq d_{v_i v_j}, \ \forall v_i v_j \in E, \tag{16}$$

where,

$$\text{distance}(w_{v_i}, w_{v_j}) = \min_{s \in w_{v_i}, t \in w_{v_j}} (|s - t| - 1).$$

DSA Examppple: Input

Table 3: Four requests in a 4-cycle EON

	Bandwidth Capacity	**Route**
Request R_1	3 FS'	B-A-D
Request R_2	2 FS'	C-B-A
Request R_3	3 FS'	A-D-C-B
Request R_4	1 FS	C-B-A-D

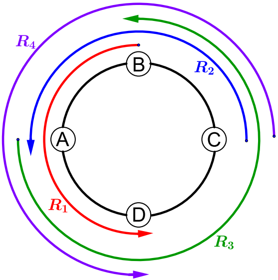
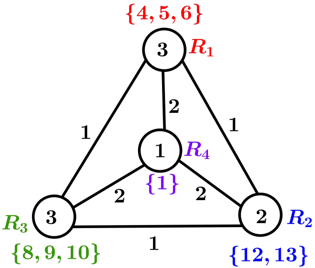
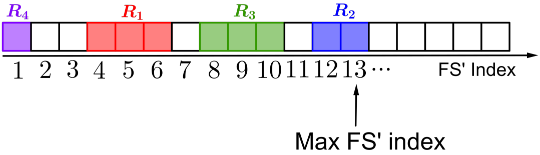


Figure 17: Explicit routes for the above table.

DSA Conflict Graph and Output





Comparison of related coloring problems

	Classical Coloring (*e.g.*, WA)	Fractional Coloring	Traditional SA	DSA (this work)
Vertex Color	One color	Set of colors	Set of colors	Set of colors
Color Contiguity	N/A	No need	Required	Required
Color Distance of Adjacent Vertices	Disjoint Disjoint	Disjoint Disjoint	Identical positive integer	Various positive integers

Hardness and Inapproximability

MHP: Minimum Hamitolion Path

Theorem 1

$MHP \leq^P DSA \Rightarrow DSA$ is $\mathcal{NP}$-hard.

Hardness and Inapproximability

MHP: Minimum Hamitolion Path

Theorem 1

MHP $\leq^P$ *DSA* $\Rightarrow$ *DSA is* $\mathcal{NP}$*-hard.*

Theorem 2

Unless $\mathcal{NP} \subset \mathcal{ZPP}$, *no polynomial-time DSA heuristic algorithm APX can guarantee* $\frac{APX(\mathcal{I})}{OPT(\mathcal{I})}$ *within* $\mathcal{O}(n^{1-\epsilon})$ *for all instances* $\mathcal{I}$, *where n is the number of vertices of* $\mathcal{I}$ *and* $\epsilon > 0$.

Upper and Lower Bounds

- $|opt(G)|$: optimal solution of DSA problem
- $\chi(G)$: chromatic number of G
- $\Delta(G)$: maximum nodal degree, $\chi(G) \leq \Delta(G) + 1$
- $\psi \in \Psi(G)$: maximal clique / clique set
- $MHP(\psi)$: minimum Hamilton path length in ψ
- ψ^w: sum of node weights in ψ

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- $MHP(\psi)$: minimum Hamilton path length in ψ
- ψ^w: sum of node weights in ψ

Theorem 3

Given any DSA conflict graph G, inequality (17) is held for the optimal solution of the DSA problem.

$$\max_{\psi \in \Psi(G)} \{|MHP(\psi)| + \psi^w\} \leq |opt(G)| \leq \sum_{i=1}^{\chi(G)-1} d_{e'_i} + \sum_{i=1}^{\chi(G)} v_i'^w. \tag{17}$$

Upper and Lower Bounds

- $|opt(G)|$: optimal solution of DSA problem
- $\Delta(G)$: maximum nodal degree in G, $\chi(G) \leq \Delta(G) + 1$

Corollary 4

If $G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$ *is a DSA graph, then* $|opt(G)| \leq \sum_{i=1}^{\Delta(G)} d_{e_i} + \sum_{i=1}^{\Delta(G)+1} v_i^w$.

Two-phased Algorithm

$$G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$$

First phase

Deterministic algorithm: FPGA

Time complexity: $\mathcal{O}(|V|^3\Delta)$

where Δ is the maximum degree of G

Initial solution

Second phase

Random optimization algorithm: SPNP

Convergence and the expect iterations

To improve the initial solution

Final solution

Algorithm Analysis

First Phase Greedy Algorithm (FPGA):

Theorem 5

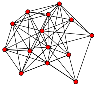
If $G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$ is a complete DSA graph with triangle inequality then the approximation ratio of FPGA is not bigger than $\frac{1}{2}(\lceil \log_2 |V| \rceil + 1)$.

Theorem 6

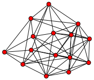
If a DSA graph $G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$ is a bipartite graph whose vertex label is well, then FPGA can get the optimal solution of G.

The Numerical Results

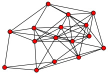
Two-phase algorithm is compared with FPGA, ILP and PRA.



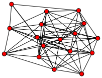
(a) 14



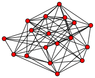
(b) 15



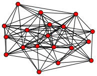
(c) 16



(d) 17



(e) 18



(f) 19

Figure 18: Six random graphs with 14-19 vertices.

Table 4: Numerical results for six random graphs

# vertex	14	15	16	17	18	19
PRA	92.0	103.	101.	133.	125.	180.
FPGA	72.4	76.6	83.4	94.2	89.8	126.
Two-phase	69.0	74.4	81.6	91.2	88.2	124.
ILP-DSA	67.4	72.4	79.6	88.8	83.8	116.

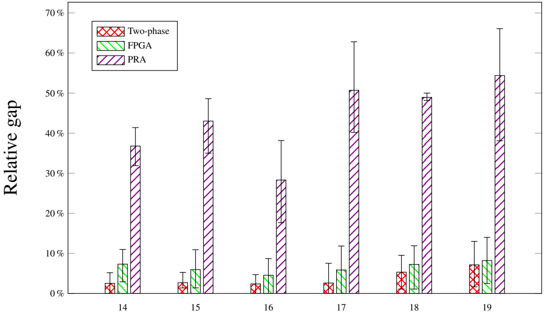


Figure 19: Relative gaps by Two-phase, FPGA and PRA.

Table 5: Numerical results for random complete graphs

# vertices	14	15	16	17	18	19
PRA	168.8	193.8	237.6	238.6	283.0	290.3
FPGA	144.6	164.2	197.2	199.4	229.6	238.3
Two-phase	143.2	163.2	196.2	196.6	226.8	233.6
ILP-DSA	142.2	160.4	194.0	194.2	223.2	224.0

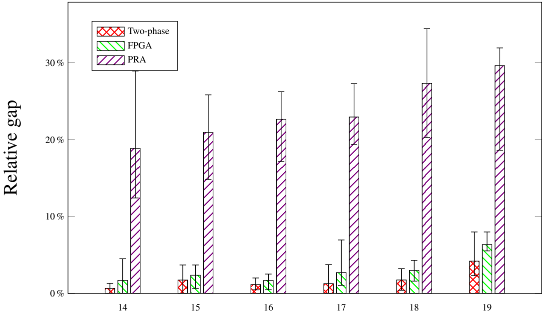


Figure 20: Relative gaps by Two-phase, FPGA and PRA.

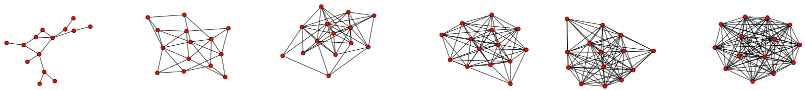


Figure 21: Six random graphs with 14 vertices cum edge number from 15 to 90

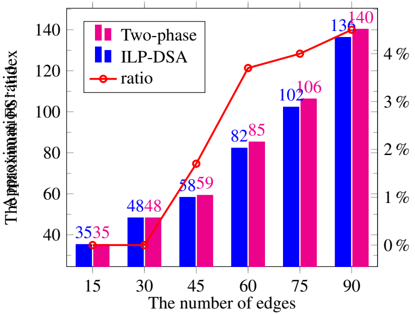


Figure 22: Numerical results for Edge number scenario.

Table 6: Simulation results for NSFNET and US Backbone

NSFNET				US Backbone			
# request	**ILP-DSA**	**Two-phased**	**PRA**	**# request**	**ILP-DSA**	**Two-phased**	**PRA**
10	29	29	29	10	33	33	33
20	72	72	76	30	186	189	197
30	153	153	177	50	351	363	462
40	200	201	252	100	—	1339	1898
50	420	423	500	150	—	2843	4666
60	—	469	602	200	—	3784	7743
70	—	598	805	250	—	6347	13020
80	—	890	1155	300	—	8140	17303

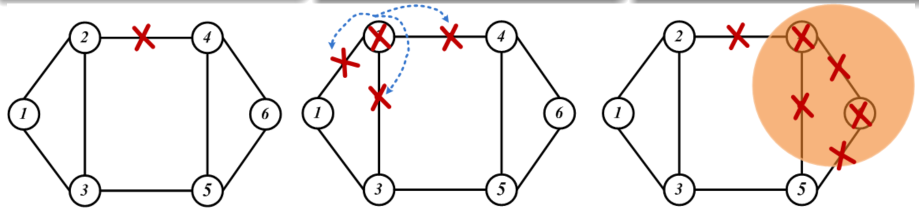
Summary

DSA in EONs

- NP-Hard and inapproximability
- Lower and upper bounds
- Near optimal two-Phase algorithm

Optical DCNs Survivability (Thesis of Min JU)

- **Link Failure**
  Construction, damaged connectors ... ...
- **Node Failure**
  Node equipment failure (transponder, switching) ... ...
- **Large Area Disaster**
  Datacenter system damage, earthquake, flood ... ...



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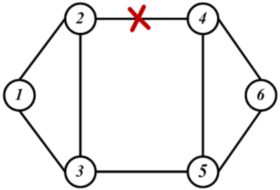

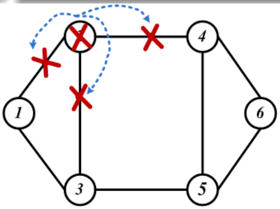

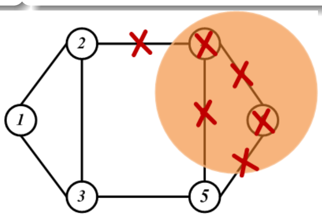


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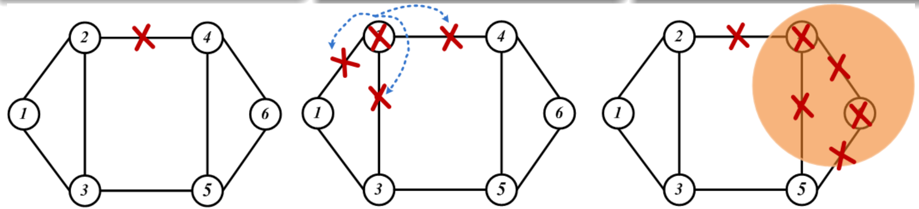
- **Large Area Disaster**

Datacenter system damage, earthquake, flood ... ...



Most common!!

Threat on Datacenter networks!!

Optical DCNs Survivability (Thesis of Min JU)

- **Link Failure**

Construction, damaged connectors ... ...

- **Node Failure**

Node equipment failure (transponder, switching) ... ...

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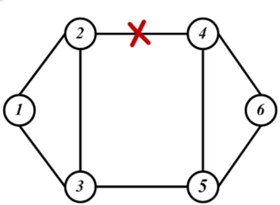
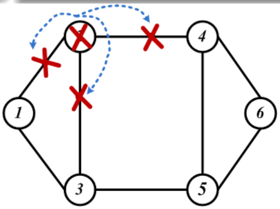
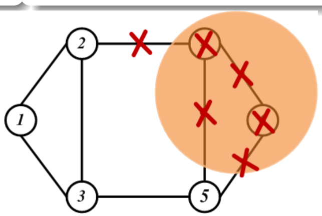
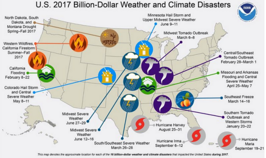






Cables were cut by ship, 2017, Somalia, $10 million/day

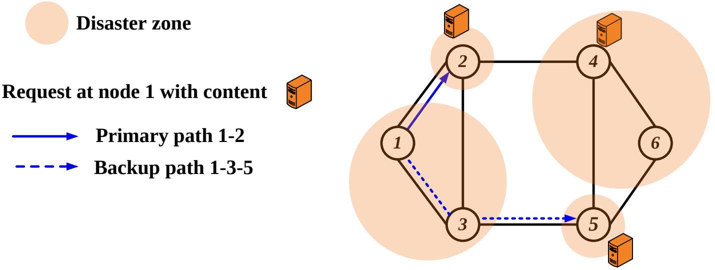


Weather and climate disasters, 2017, USA, $306 billion

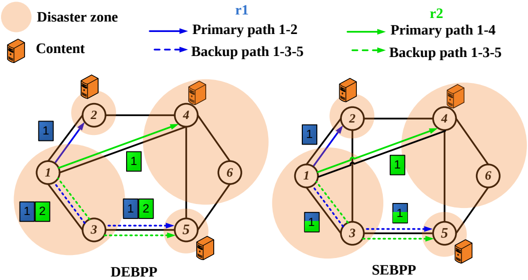
A "power surge" in one British Airways' datacenter, 2017

Large Area Disaster Failure in Datacenter Networks

- Disasters: Volcan, Tsunamis, Hurricane, Flood, etc
- Disaster zones: Set of OXC nodes and fibers
- DC content survivability
- Disaster-disjoint primary path and backup path



Path Protection against Disaster Failure



- Data center with content replia
  - The same content can be replicated at multiple DC nodes.
- Anycast routing, *i.e.*, from one to one of many
  - One to one of many: the service can be provisioned from any of the DC with content replica.

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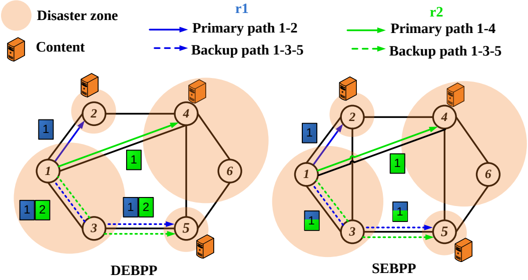

- Data center with content replia
  - The same content can be replicated at multiple DC nodes.
- Anycast routing, *i.e.*, from one to one of many
  - One to one of many: the service can be provisioned from any of the DC with content replica.
- DEBPP (Dedicated end-to-content backup path protection)
- SEBPP (Shared end-to-content backup path protection)

Disaster-aware Path Protection Schemes in the Literature

	ILP	Heuristics
SLR WDM	[C. Develder et al, Trans. Netw., 2014] [M. F. Habib et al, J. Lightw. Technol., 2012] [S. S. Savas et al, Photon. Netw. Commun., 2014] [S. S. Savas et al, Photon. Netw. Commun., 2016]	[C. Develder et al, Trans. Netw., 2014] [M. F. Habib et al, J. Lightw. Technol., 2012] [S. S. Savas et al, Photon. Netw. Commun., 2014] [S. S. Savas et al, Photon. Netw. Commun., 2016]
EON	[R. Xu et al, Optoel. Global Conf., 2016] [C. Ma et al, Photon. Netw. Commun., 2015] [X. Li et al, Opt. Express, 2016]	[C. Ma et al, Photon. Netw. Commun., 2015] [X. Li et al, Opt. Express, 2016] [B. Chen et al, Photon. Netw. Commun., 2017]

- ILP formulation: not scalable
- Heuristics: not tractable
- Impacts of No. DC and replica: not yet studied
- Comparison of protection techniques: missing

Objective and Constraints

Inputs:

- Set of disaster zones (DZs)
- Set of requests and their required content
- Number of DCs and content replica (k)
- EON topology and set of FSs

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Objective: Minimize total spectrum usage for disaster protection

- Single disaster zone protection
- DEBPP vs. SEBPP
- Impacts of No. Dc and replica
- Scalable and tractable approach

Methodology 1: Joint ILP Formulation

Ojective:

$$\textit{Minimize} \quad \overbrace{\theta_1 \cdot (\sum_{a \in A} \sum_{r \in R} p_{ra}^W \cdot \phi_r + \sum_{a \in A} T_a)}^{\text{Link-FSs}} + \overbrace{\theta_2 \cdot \Delta}^{\text{Max-FSs}}$$

Constraints:

- (1) Datacenter and content assignment
- (2) Disaster-disjoint path generation
- (3) Spectrum allocation

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Constraints:

- (1) Datacenter and content assignment
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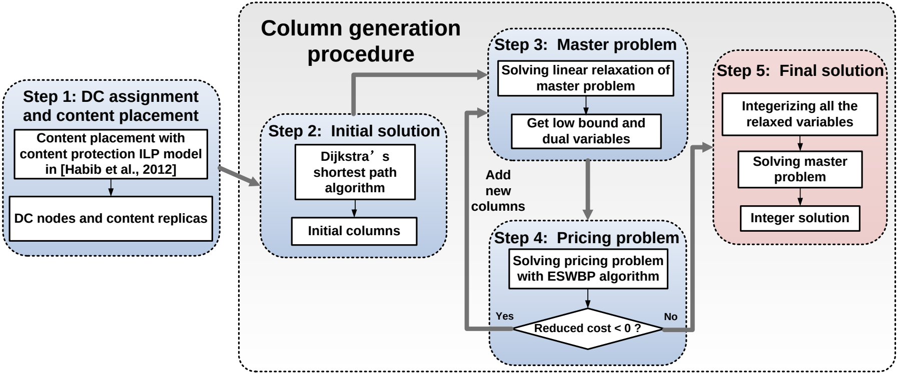
- (3) Spectrum allocation

Computational complexity

- DEBPP
  - No. of dominant variables $O(|R|^2, |R||A|, |R||Z|, |C||D|)$
  - No. of dominant constraints $O(|R|^2|A|, |R||Z||A|)$
- SEBPP
  - No. of dominant variables $O(|R|^2, |R||A|, |R||Z|, |C||D|)$
  - No. of dominant constraints $O(|R|^2|A|, |R|^2|Z|, |R||Z||A|)$

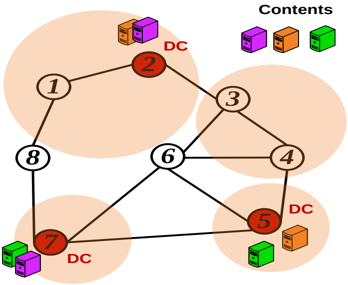
Methodology 2: Column Generation (CG)



Advantages of CG

- Scalable iterative optimization
- Lower bound z^*
- ρ-optimum, $\rho \leq (z - z^*)/z^*$

Methodology 2: Column Generation (CG)

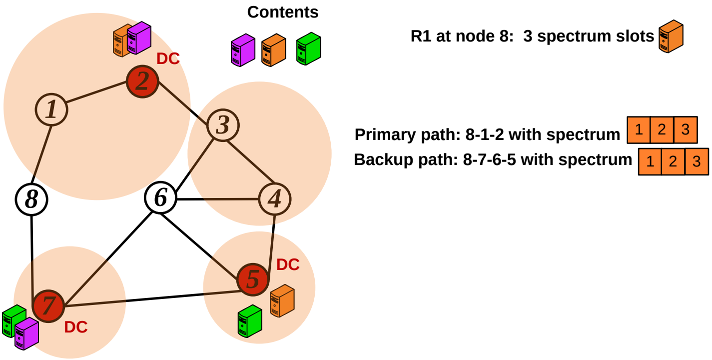


Step 1: DC assignment and content placement

- K DC nodes: Average minimum distance
- Place content replica in DCs closer to its popular region

Habib et al. Design of disaster-resilient optical DC networks. J. Lightw. Technol., 2012.

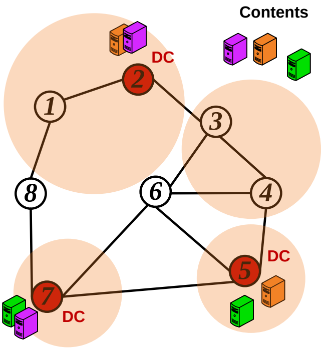
Methodology 2: Column Generation (CG)

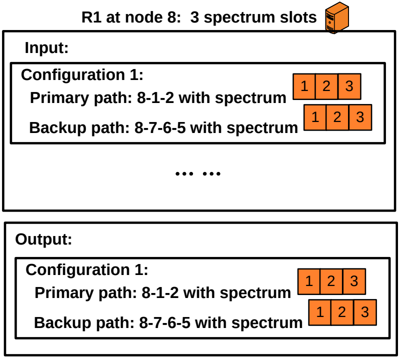


Step 2: Initial solution

- Primary path and backup path via Dijkstra's shortest path
- Spectrum usage allocation with coloring heuristic

Methodology 2: Column Generation (CG)

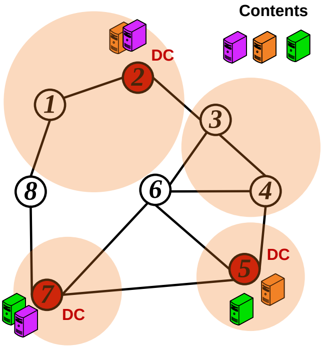




Step 3: Master problem

- A configuration ω_r for request r:
  1. Primary path and backup path
  2. Spectrum usage for primary and backup paths
- Input: $\forall r \in R$, ω_r
- Output: Final primary and backup paths and associated spectrum

Methodology 2: Column Generation (CG)



R1 at node 8: 3 spectrum slots

Configuration 1:
Primary path: 8-1-2 with spectrum 1 2 3
Backup path: 8-7-6-5 with spectrum 1 2 3

Output:

New configuration 2:
Primary path: 8-1-2 with spectrum 1 2 3
Backup path: 8-7-5 with spectrum 1 2 3

New configuration 3:
Primary path: 8-1-2 with spectrum 2 3 4
Backup path: 8-7-5 with spectrum 1 2 3

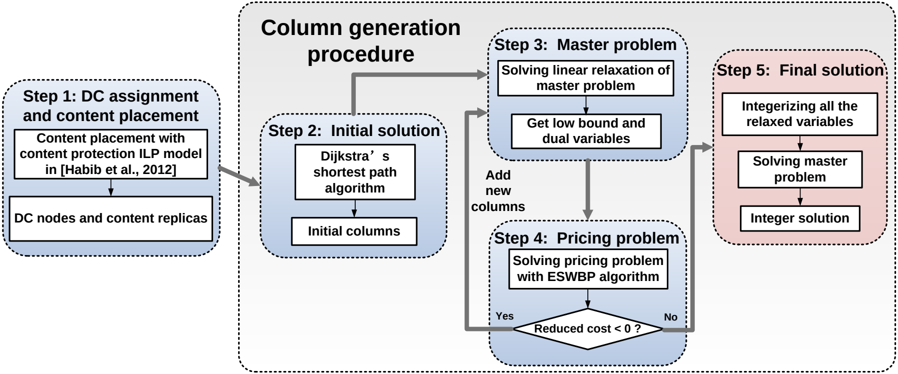
... ...

Step 4: Pricing problem (k shortest paths)

- Input: R, $G(V, A)$, Disaster zones
- Output: Configuration $\omega_r, \forall r \in R$

1. Primary path and backup path of $\forall r \in R$
2. Spectrum usage on primary path of $\forall r \in R$
3. Spectrum usage on backup path of $\forall r \in R$

Methodology 2: Column Generation (CG)

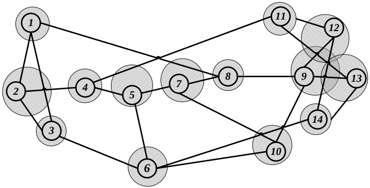


Step 5: Final solution

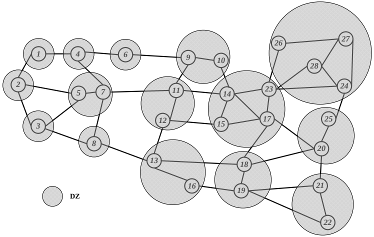
- Convert all variables to integer
- Solve the master problem again

Numerical results: Simulation settings

- NSFNET network
  14 nodes, 44 links
  3.1 nodal degree, 14 DZs



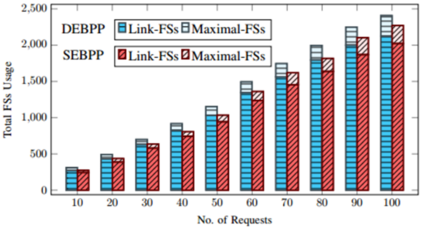
- US Backbone network
  28 nodes, 90 links
  3.2 nodal degree, 15 DZs



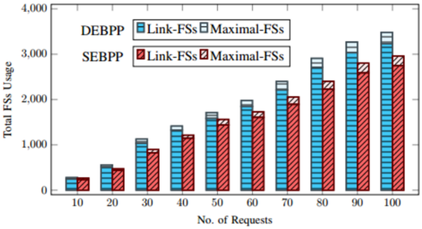
- Hardware: 3.5 GHz CPU, 8 GBytes RAM
- Software: CPLEX 12.06
- Traffic
  - FSs: randomly [1, 10]
  - No. requests: [10, 100]
- Parameters:
  - 300 Available FSs
  - 10 Available content
  - content replicas K

Spectrum usage of DEBPP and SEBPP vs. # requests

No. Requests		Joint ILP models				CG approach							Gap
		z_{1h}^{ILP}	FS_{total}	FS_{link}	t^{ILP}	z^{LP}	z_{1h}^{CG}	FS_{link}	FS_{max}	t^{CG}	t_{LPR}^{CG}	t_{ILP}^{CG}	
10	DEBPP	**290**	260	30	$8s$	312	**312**	270	42	$1s$	$1s$	$0s$	**7.59%**
	SEBPP	**253**	233	20	$448s$	275	**275**	243	32	$5s$	$5s$	$0s$	**8.70%**
20	DEBPP	**448**	412	36	$3600s$	488	**493**	431	62	$6s$	$6s$	$0s$	**10.04%**
	SEBPP	**379**	345	34	$3600s$	424.733	**432**	388	44	$7s$	$7s$	$0s$	**13.98%**
30	DEBPP	**663**	613	50	$3600s$	691.998	**700**	630	70	$7s$	$7s$	$0s$	**5.58%**
	SEBPP	**614**	570	44	$3600s$	608	**630**	572	58	$23s$	$23s$	$0s$	**2.61%**
40	DEBPP	**867**	792	75	$3600s$	898.389	**912**	826	86	$54s$	$8s$	$46s$	**5.19%**
	SEBPP	**832**	765	67	$3600s$	761.612	**792**	719	73	$49s$	$44s$	$5s$	-



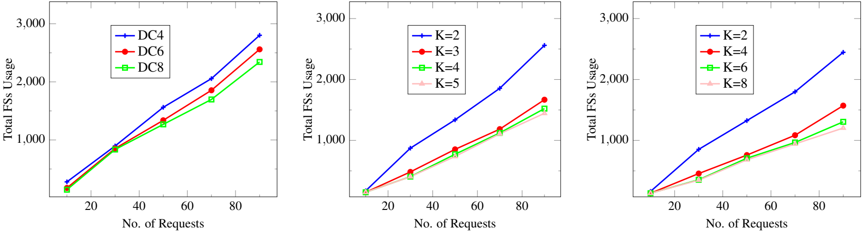
(a) Total FSs Usage in NSFNET



(b) Total FSs Usage in US Backbone

SEBPP spectrum usage vs. # DCs and # content replica K

US Backbone	
No. of DCs	Location of DCs
4	Nodes 1, 12, 21, 28
6	Nodes 1, 7, 14, 19, 21, 28
8	Nodes 1, 7, 9, 12, 14, 19, 21, 28
10	Nodes 1, 3, 7, 9, 12, 14, 19, 21, 24, 28



(a) FSs vs. # DCs (b) FSs vs. # K (6 DCs) (c) FSs vs. # K (8 DCs)

Summary of Disaster Protection

Comparison of Protection Techniques

- Spare capacity efficiency: SEBPP $>$ DEBPP $>$ p-Cycle
- Recovery speed: DEBPP $>$ p-Cycle $>$ SEBPP
- DEBPP vs. SEBPP, less spectrum usage, higher computation complexities.

Impacts on Spectrum usage

- Reasonable $\#$ DCs, $\rightarrow$ spectrum savings.
- Reasonable $\#$ content replica $k \rightarrow$ spectrum savings.

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Optimization

- ρ-optimum CG approach
- Scalable for large disaster failure in DCNs
- Path generation
- Spectrum allocation

Conclusions

1: Video Delivery in Telco-CDNs

- Overlay construction (Thesis of J. Liu)
- Bandwidth allocation

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$\Downarrow$

Optimization of routing and resource allocation

- Tools: ILP, CG, heuristic, approximation algorithm
- Optimization techniques do help!

Perspectives

Similar optimization techniques will also be helpful to solve:

$$\Downarrow$$

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Physical-layer security in EONs

- Threats: attacks, interferences
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QoE for 360 video streaming

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- Road security via VANETs
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$+$ new direction

Bi-level optimization for ITS and green networking.


Thank you!


MERCI


谢谢


QUESTIONS ?

Overview of Research Activities

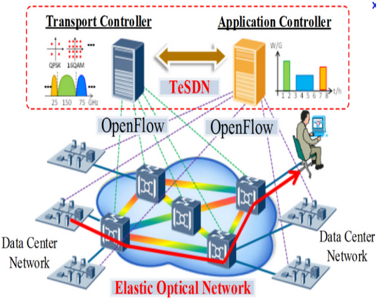
Routing optimization and resource allocation

- Optical networks, RF/VLC HetNets
- Wireless ad-hoc networks (VANET, WSN et MANET)
- Content delivery networks
- Intelligent transportation systems

Optical Networks and Datacenter Networks

Problems

- Routing and spectrum assignment (RSA)
- Survivability and security
- Multicast, network function virtualization,



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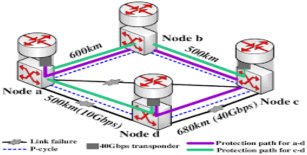

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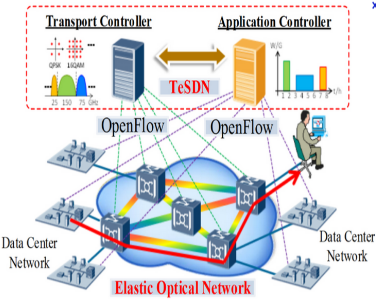

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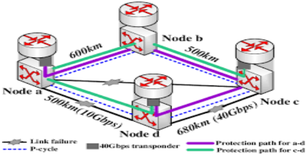
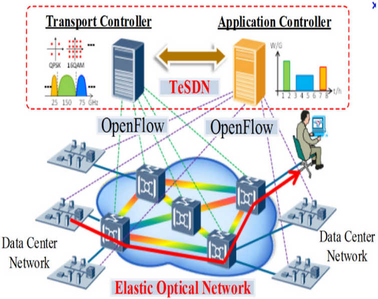
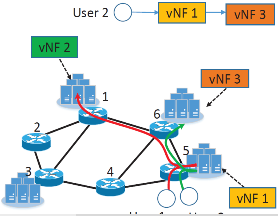


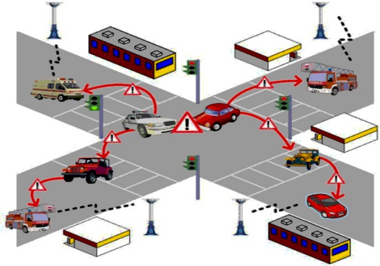




Wireless Ad-Hoc Networks

Problems

- VANETs: Routing for the dissemination of safety messages
- WSNs: Data gathering and aggregation



Wireless Ad-Hoc Networks

Problems

- VANETs: Routing for the dissemination of safety messages
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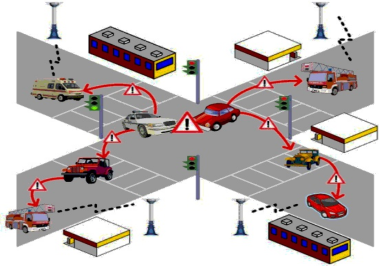
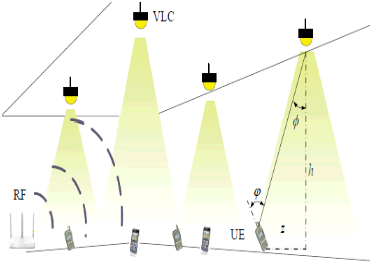
Problems

- MANETs: Malicious node detection
- RF/VLC HetNets: Resource allocation





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Problems

- Video streaming using *rateless coding*
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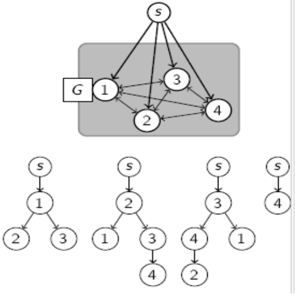

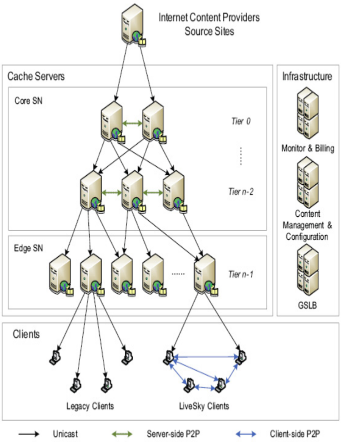

Intelligent Transportation Systems (ITS)

Problems

- Car relocation optimization for car-sharing systems
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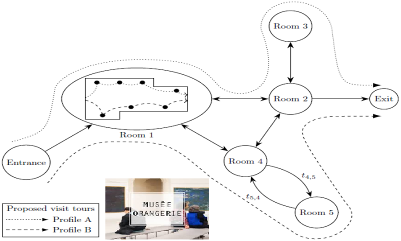

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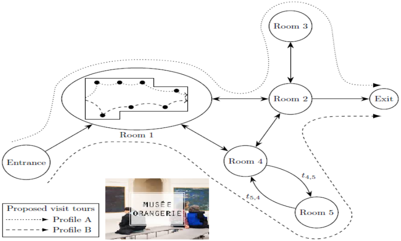
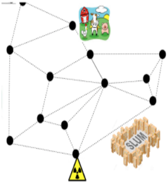
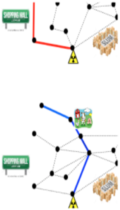






MILP for FAM

$$\max \quad L \qquad \text{(FAM-MIP)} \tag{18}$$

s.t. constraints (19)-(27).

$$\sum_{v \in V} \sum_{a \in \delta^+(v)} X_a = n, \tag{19}$$

$$\sum_{a \in \delta^-(s)} F_a = n, \tag{20}$$

$$\sum_{a \in \delta^+(v)} F_a - \sum_{a \in \delta^-(v)} F_a = 1, \qquad \forall v \tag{21}$$

$$X_a \leq F_a, \qquad \forall a \tag{22}$$

$$X_a \geq \frac{1}{n} F_a, \qquad \forall a \tag{23}$$

$$\frac{\sum_{a \in \delta^-(v)} X_a - i + \frac{1}{2}}{d_v} \leq B_v^i, \qquad \forall v, \forall i \in [\![d_v - 1]\!] \tag{24}$$

$$\frac{\sum_{a \in \delta^-(v)} X_a - i + \frac{1}{2}}{d_v} \geq B_v^i - 1, \qquad \forall v, \forall i \in [\![d_v - 1]\!] \tag{25}$$

$$\frac{E_v - (e^t + i \cdot e^r) L_v}{M_v^1} \geq B_v^i - 1, \qquad \forall v, \forall i \in [\![d_v - 1]\!] \tag{26}$$

$$L \leq L_v, \qquad \forall v \tag{27}$$

MILP for NAM

$$\max \quad L \qquad \text{(NAM-MIP)} \tag{28}$$

s.t. constraints (29)-(37).

$$\sum_{v\in V}\sum_{a\in\delta^+(v)} X_a = n, \tag{29}$$

$$\sum_{a\in\delta^-(s)} F_a = n, \tag{30}$$

$$\sum_{a\in\delta^+(v)} F_a - \sum_{a\in\delta^-(v)} F_a = 1, \qquad \forall v \tag{31}$$

$$X_a \le F_a, \qquad \forall a \tag{32}$$

$$X_a \ge \frac{1}{n}F_a, \qquad \forall a \tag{33}$$

$$\frac{\sum_{a\in\delta^-(v)} F_a - i + \frac{1}{2}}{n} \le B_v^i, \qquad \forall v, \forall i \in [\![n-1]\!] \tag{34}$$

$$\frac{\sum_{a\in\delta^-(v)} F_a - i + \frac{1}{2}}{n} \ge B_v^i - 1, \qquad \forall v, \forall i \in [\![n-1]\!] \tag{35}$$

$$\frac{E_v - \left(e^t + i(e^t + e^r)\right)L_v}{M_v^2} \ge B_v^i - 1, \forall v, \forall i \in [\![n-1]\!] \tag{36}$$

$$L \le L_v, \qquad \forall v \tag{37}$$

MILP for HAM (part 1)

Flow Constraints

$$\max \quad L \qquad \text{(HAM-MIP)} \tag{38}$$

s.t. constraints (39)-(52).

$$\sum_{v \in V} \sum_{a \in \delta^+(v)} X_a = n, \tag{39}$$

$$\sum_{a \in \delta^-(v)} \hat{F}_a \leq (k-1) + (n-k) H_v^k, \qquad \forall v \tag{40}$$

$$\sum_{a \in \delta^-(v)} \hat{F}_a \geq k \cdot H_v^k, \qquad \forall v \tag{41}$$

$$\sum_{a \in \delta^+(v)} \hat{F}_a - \sum_{a \in \delta^-(v)} \hat{F}_a \geq 1 - (n-k) H_v^k, \qquad \forall v \tag{42}$$

$$\sum_{a \in \delta^+(v)} \hat{F}_a \geq (k-1) H_v^k + 1, \qquad \forall v \tag{43}$$

$$X_a \geq \frac{1}{k} \hat{F}_a, \qquad \forall a \tag{44}$$

$$X_a \leq \hat{F}_a, \qquad \forall a \tag{45}$$

MILP for HAM (part 2)

Energy Constraints (Linearization)

$$\max \quad L \qquad \text{(HAM-MIP)} \tag{46}$$

s.t. constraints (39)-(52).

$$\frac{E_v - (i \cdot e^t + j \cdot e^r)L_v}{M_v^3} \geq B_v^i + B_v^j - 2, \qquad \forall v, \forall i \in [\![k]\!], \forall j \in [\![n-1]\!] \tag{47}$$

$$\frac{\sum_{a \in \delta^+(v)} \hat{F}_a - i + \frac{1}{2}}{k+1} \leq B_v^i, \qquad \forall v, \forall i \in [\![k]\!] \tag{48}$$

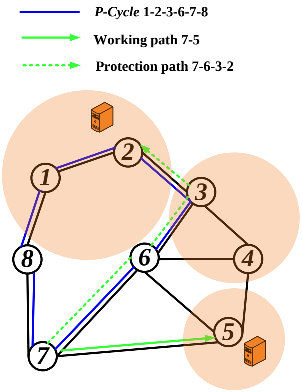
$$\frac{\sum_{a \in \delta^+(v)} \hat{F}_a - i + \frac{1}{2}}{k+1} \geq B_v^i - 1, \qquad \forall v, \forall i \in [\![k]\!] \tag{49}$$

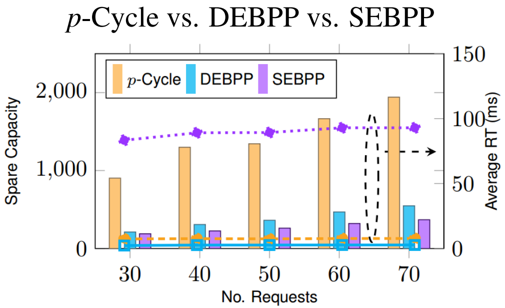
$$\frac{\sum_{a \in \delta^-(v)} \hat{F}_a - j + \frac{1}{2}}{n} \leq B_v^j, \qquad \forall v, \forall j \in [\![n-1]\!] \tag{50}$$

$$\frac{\sum_{a \in \delta^-(v)} \hat{F}_a - j + \frac{1}{2}}{n} \geq B_v^j - 1, \qquad \forall v, \forall j \in [\![n-1]\!] \tag{51}$$

$$L \leq L_v, \qquad \forall v \tag{52}$$

Why not *p*-Cycle Protection?





Drawbacks: Waste spare capacity

- Backup Datacenter on *p*-cycle
- Inefficient spare capacity sharing

Disaster Failure: Joint ILP Formulation—DEBPP & SEBPP

Ojective:

Link-FSs | Max-FSs

$$Minimize \quad \theta_1 \cdot (\sum_{a\in A}\sum_{r\in R} p_{ra}^W \cdot \phi_r + \sum_{a\in A} T_a) + \theta_2 \cdot \Delta$$

Constraints

1.DC assignment and content placement constraints

$$\sum_{d\in D} \Lambda_{rd}^W = 1, \qquad \forall r \qquad (53)$$

$$\sum_{d\in D} \Lambda_{rd}^B = 1, \qquad \forall r \qquad (54)$$

$$\sum_{d\in D} R_d^c \leq K, \qquad \forall c \qquad (55)$$

$$\Lambda_{rd}^W + \Lambda_{rd}^B \leq R_d^{c_r}, \qquad \forall r, \forall d \qquad (56)$$

2.Flow-conservation constraints

$$\sum_{a\in\Psi_v^+} p_{ra}^W - \sum_{a\in\Psi_v^-} p_{ra}^W = \begin{cases} 1, & v = s_r \\ -\Lambda_{rv}^W, & v \in D, \\ 0, & \text{otherwise} \end{cases} \qquad \forall r, \forall v. \qquad (57)$$

$$\sum_{a\in\Psi_v^+} p_{ra}^B - \sum_{a\in\Psi_v^-} p_{ra}^B = \begin{cases} 1, & v = s_r \\ -\Lambda_{rv}^B, & v \in D, \\ 0, & \text{otherwise} \end{cases} \qquad \forall r, \forall v. \qquad (58)$$

Disaster Failure: Joint ILP Formulation—DEBPP+SEBPP

Ojective:

$$Minimize \quad \underbrace{\theta_1 \cdot (\sum_{a\in A}\sum_{r\in R} p^W_{ra}\cdot\phi_r + \sum_{a\in A} T_a)}^{\text{Link-FSs}} + \overbrace{\theta_2 \cdot \Delta}^{\text{Max-FSs}}$$

Constraints

3.Disaster-zone-disjoint path constraints

$$\alpha^W_{rz} \le \sum_{a\in z} p^W_{ra}, \quad \forall r, \forall z \tag{59}$$

$$\alpha^W_{rz} \ge p^W_{ra}, \quad \forall r, \forall z, \forall a \in z \tag{60}$$

$$\alpha^B_{rz} \le \sum_{a\in z} p^B_{ra}, \quad \forall r, \forall z \tag{61}$$

$$\alpha^B_{rz} \ge p^B_{ra}, \quad \forall r, \forall z, \forall a \in z \tag{62}$$

$$\alpha^W_{rz} + \alpha^B_{rz} \le 1, \quad \forall r, \forall z \tag{63}$$

4.Spectrum allocation constraints

$$p^W_{ra} + p^W_{r'a} - 1 \le \gamma^W_{rr'}, \quad \forall r, r', r > r', \forall a \tag{64}$$

$$\gamma^W_{rr'} = \gamma^W_{r'r}, \quad \forall r, r', r > r' \tag{65}$$

$$p^B_{ra} + p^B_{r'a} - 1 \le \gamma^B_{rr'}, \quad \forall r, r', r > r', \forall a \tag{66}$$

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$$p^W_{ra} + p^B_{r'a} - 1 \le \gamma^{WB}_{rr'}, \quad \forall r, r', r \ne r', \forall a \tag{68}$$

$$\beta^W_{rr'} + \beta^W_{r'r} = 1, \quad \forall r, r', r > r' \tag{69}$$

$$\beta^B_{rr'} + \beta^B_{r'r} = 1, \quad \forall r, r', r > r' \tag{70}$$

$$g^W_r + \phi_r \le \Delta, \quad \forall r \tag{71}$$

$$g^B_r + \phi_r \le \Delta, \quad \forall r \tag{72}$$

Disaster Failure: Column Generation (CG)

Step 1: DC assignment

$$\textit{Minimize} \quad \sum_{d\in V'} \sum_{r\in R} H_{s,d} \cdot R^{c,r}$$

$$\sum_{d\in V'} R^{c,r} = K, \qquad \forall c \tag{73}$$

$$\sum_{d\in z} R^{c,r} \leq 1, \qquad \forall c, \forall z \tag{74}$$

[a]

[a] Farhan Habib, et al, J.Lightw. Technol., 2012.

Step 2: Initial solution

- Computing Initial primary path and backup path
  1. for each r
  2. Traditional Dijkstra's shortest path to compute primary path
  3. Calculate threat disaster zones
  4. remove all the links in the threat disaster zones
  5. Traditional Dijkstra's shortest path to compute backup path
- Allocation spectrum usage
  1. Construct the conflict graph among the primary path and backup paths
  2. Coloring heuristic

Disaster Failure: Column Generation (CG)

Step 3: Master problem

- Spectrum channel H: a set of contiguous spectrum.
  For example, H for a request with 2 FSs:
  $\{1, 1, 0, 0, 0, ..., 0, 0\}$,$\{0, 1, 1, 0, 0, ..., 0, 0\}$,$\{0, 0, 1, 1, 0, ..., 0, 0\}$,
  $\cdots\cdots$,$\{0, 0, 0, 0, 0, ..., 1, 1\}$.
- A configuration ω_r for request r:
  1. primary path and backup path
  2. spectrum channels for primary and backup paths
- Variables:
  1. $q_r^\omega \in \{0, 1\}$: Equals 1 if ω-th configuration for request r is used including the working path, backup path and assigned channels, and 0 otherwise.
  2. $e_{af} \in \{0, 1\}$: Equals 1 if link a with FS f is used by the working or backup paths of all the requests, and 0 otherwise.
  3. $o_f \in \{0, 1\}$: Equals 1 if FS f is used, and 0 otherwise.

Disaster Failure: Column Generation (CG)

Step 3: Master problem

Ojective:

Link-FSs Max-FSs

$$\textit{Minimize} \quad \boxed{\theta_1 \cdot \sum_{a\in A}\sum_{f\in S} e_{af}} + \boxed{\theta_2 \cdot \sum_{f\in S} o_f}$$

Constraints:

1.DEBPP

$$\sum_{\omega\in\Omega_r} q_r^\omega = 1, \qquad \forall r \qquad (75)$$

$$\sum_{r\in R}\sum_{\omega\in\Omega_r} (p^W_{\omega rah} + p^B_{\omega rah'}) \cdot q_r^\omega \le e_{af}, \qquad \forall a, \forall f \in B_h, B_{h'} \qquad (76)$$

$$o_f \ge e_{af}, \qquad \forall a, \forall f \qquad (77)$$

$$o_f \ge o_{f+1}, \qquad \forall f \qquad (78)$$

2.SEBPP

$$\sum_{\omega\in\Omega_r} q_r^\omega = 1, \qquad (79)$$

$$\sum_{r\in R}\sum_{\omega\in\Omega_r} p^W_{\omega rah} \cdot q_r^\omega \le e_{af}, \qquad \forall a, \forall f \in B_h \qquad (80)$$

$$\sum_{r\in R}\sum_{\omega\in\Omega_r} \{p^W_{\omega rah} \cdot (1-\alpha^W_{\omega rz}) + p^B_{\omega rah'} \cdot \alpha^W_{\omega rz}\} \cdot q_r^\omega \le e_{af}, \qquad \forall a, \forall f \in B_h, B_{h'}, \forall z \qquad (81)$$

$$o_f \ge e_{af}, \qquad (82)$$

$$o_f \ge o_{f+1}, \qquad (83)$$

Disaster Failure: Column Generation (CG)

Step 4: Pricing problem

- Dual variables:
  1. μ_r : dual variable for DEBPP and SEBPP
  2. $\zeta_{af} \geq 0$: dual variable for DEBPP
  3. $\rho_{af} \geq 0$: dual variable for SEBPP
  4. $\eta_{afz} \geq 0$: dual variable for SEBPP
- Reduced cost for DEBPP:

$$\bar{c}_{\omega_r}^{DEBPP} = 0 - \{\mu_r - \sum_{a \in A} \sum_{f \in B_h \cup B_{h'}} (p_{\omega rah}^W + p_{\omega rah'}^B) \cdot \zeta_{af}\} = -\mu_r + \sum_{a \in A} p_{\omega rah}^W \cdot Cost_{\omega rah}^W + \sum_{a \in A} p_{\omega rah'}^B \cdot Cost_{\omega rah'}^B$$

$$Cost_{\omega rah}^W = \sum_{f \in B_h} \zeta_{af} \qquad Cost_{\omega rah'}^B = \sum_{f \in B_{h'}} \zeta_{af} \tag{84}$$

- Reduced cost for SEBPP:

$$\bar{c}_{\omega_r}^{SEBPP} = 0 - \left(\mu_r - \sum_{a \in A} \sum_{f \in B_h} p_{\omega rah}^W \cdot \rho_{af} - \sum_{a \in A} \sum_{f \in B_h \cup B_{h'}} \sum_{z \in Z} \left\{ p_{\omega rah}^W \cdot (1 - \alpha_{\omega rz}^W) - p_{\omega rah'}^B \cdot \alpha_{\omega rz}^W \right\} \cdot \eta_{afz} \right)$$

$$= -\mu_r + \sum_{a \in A} p_{\omega rah}^W \cdot Cost_{\omega rah}^W + \sum_{a \in A} p_{\omega rah'}^B \cdot Cost_{\omega rah'}^B \tag{85}$$

$$Cost_{\omega rah}^W = \sum_{f \in B_h} \rho_{af} + \sum_{f \in B_h \cup B_{h'}} \sum_{z \in Z} (1 - \alpha_{\omega rz}^W) \cdot \eta_{afz} \qquad Cost_{\omega rah'}^B = \sum_{f \in B_h \cup B_{h'}} \sum_{z \in Z} \alpha_{\omega rz}^W \cdot \eta_{afz} \tag{86}$$

Disaster Failure: Column Generation (CG)

Step 4: Pricing problem

- Configuration ω_r in DEBPP
  1. For each $d \in D$
  2. For each $d' \in D, d' \neq d$
  3. For each $h \in H_r$
  4. For each $h' \in H_r$
  5. Calculate shortest path with $Cost^{W}_{\omega rah}$
  6. Calculate threat disaster zones
  7. remove all the links in the threat disaster zones
  8. Calculate shortest path with $Cost^{B}_{\omega rah'}$

- Configuration ω_r in SEBPP
  1. For each $d \in D$
  2. For each $d' \in D, d' \neq d$
  3. For each $h \in H_r$
  4. For each $h' \in H_r$
  5. Calculate K=2 shortest path with hop count
  6. Calculate threat disaster zones
  7. remove all the links in the threat disaster zones
  8. Calculate shortest path with $Cost^{B}_{\omega rah'}$

Step 5: Final solution

- Convert all variables to integer
- Solve the master problem again

Ordered Distance Spectrum Assignment (ODSA)

Giving a $G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$ with a vertex order O_i,
the beginning FS indices for each vertex are sorted in the increaseing order in the final solution i.e.,

$$O_i = (v_{i_1}, v_{i_2}, ..., v_{i_n}) : v_{i_j}^b \geq v_{i_k}^b, \forall j > k \tag{87}$$

where, $v_{i_j}^b$ and $v_{i_k}^b$ is the beginning FS' index of the contiguous FS' set assigned to v_{i_j} and v_{i_k} respectively.

Input : A DSA graph $G(V, E, \{v_i^w\}, \{d_{v_i v_j}\})$, and a vertex order $O_i = (v_{i_1}, v_{i_2}, ..., v_{i_n})$

Output: An assignment strategy for the beginning index $Seq = \{v_{i_j}^b : 1 \leq j \leq n\}$ and the maximum FS' index

$v_{i_1}^b \leftarrow 1;$

$v_{i_1}^a \leftarrow v_{i_1}^w;$

$Seq \leftarrow v_{i_1}^b;$

$j \leftarrow 2;$

while $j \leq n$ **do**

$\quad s_1 \leftarrow \max_{\forall k<j, v_{i_k} v_{i_j} \in E} \{v_{i_k}^a + d_{v_{i_k} v_{i_j}} + 1\};$

$\quad s_2 \leftarrow v_{i_{j-1}}^b;$

$\quad v_{i_j}^b \leftarrow \max\{s_1, s_2\};$

$\quad v_{i_j}^a \leftarrow v_{i_j}^b + v_{i_j}^w - 1;$

$\quad Seq \leftarrow Seq \cup \{v_{i_j}^b\};$

$\quad j \leftarrow j + 1;$

end

return Seq and $\max_{1 \leq j \leq n} (v_{i_j}^a)$

Algorithm 1: Procedure O-L

The time complexity of Procedure O-L is $\mathcal{O}(|E|)$

Theorem 7

The Procedure O-L results in an optimal spectrum assignment strategy for the ODSA.

Corollary 8

A DSA problem can be optimally solved by the Procedure O-L under certain vertex order.

Now, DSA has been transform to a Permutation-based Optimization Problem (POP).