On Balancing Middlebox Set-up Cost and Bandwidth Consumption in NFV

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1. Introduction of Middlebox

- Network Function Virtualization (NFV)
  - Technology of virtualizing network functions into software building blocks
- Middlebox: software implementation of network services
  - Improve the network performance:
    - Web proxy and video transcoder, load balancer, …
  - Enhance the security:
    - Firewall, IDS/IPS, passive network monitor, …
- Examples

Web Proxy

Firewall

NAT

Middlebox Dependency Relations [1]

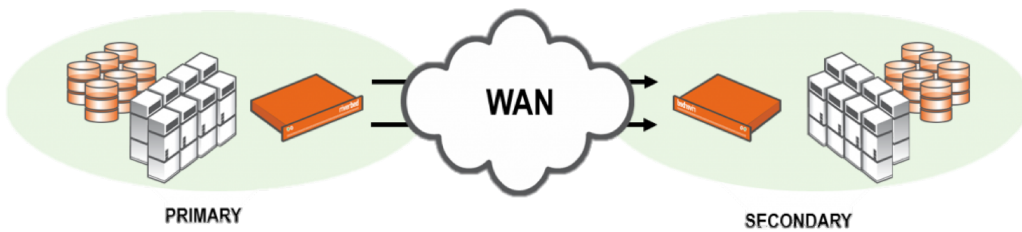
- Multiple middleboxes may/may not have a serving order
  - Examples
    - Firewall usually before Proxy
    - Virus scanner either before or after NAT gateway
- Categories
  - Non-ordered middlebox set
  - Totally-ordered middlebox set (service chain)

  - Partially-ordered middlebox set

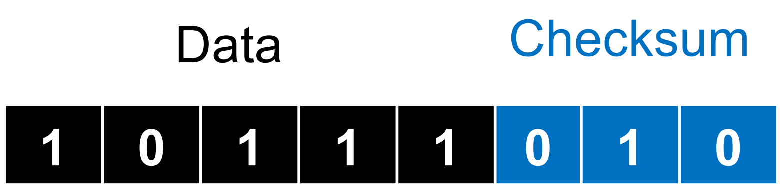
[1] Dynamic Service Function Chaining in SDN-Enabled Networks with Middleboxes (ICNP '16)

Middlebox Traffic Changing Effects [2]

- Middleboxes may change flow rates in different ways
  - Citrix CloudBridge WAN accelerator: 20% (diminishing)



  - BCH(63,48) encoder: 130% (expanding)



[2] Traffic Aware Placement of Interdependent NFV Middleboxes (INFOCOM '17)

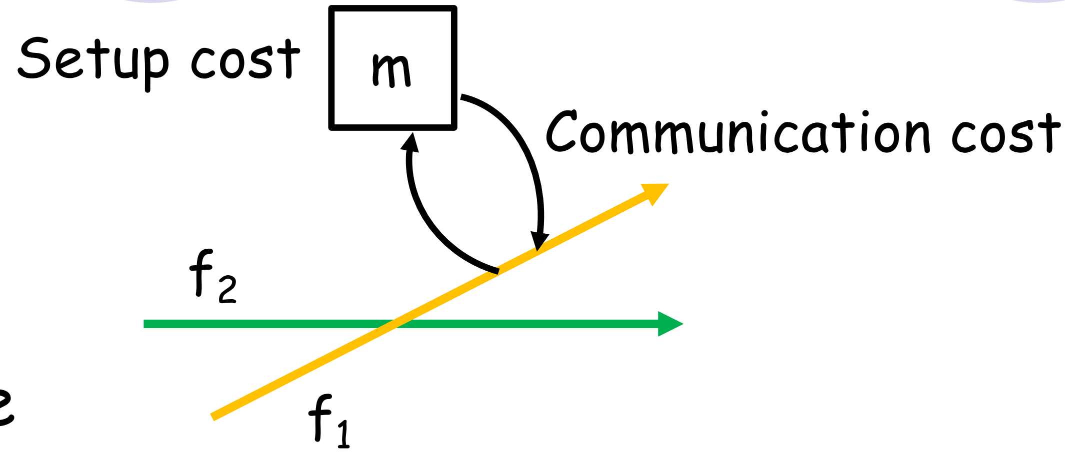
Middlebox Placement Overview

- Problem
  - Placing middleboxes to satisfy all flows' middlebox service requests
- Objectives:
  - Minimizing middlebox setup cost [3]
  - Minimizing bandwidth consumption [2]
- Constraints
  - Dependency relations
  - Traffic-changing effects
  - Vertex capacity and middlebox processing volume

[2] Traffic Aware Placement of Interdependent NFV Middleboxes (INFOCOM '17)
[3] Provably Efficient Algorithms for Joint Placement and Allocation of Virtual Network (INFOCOM '17)

A Middlebox Placement Model [4]

- Cost



- Objective
  - Minimizing sum of middlebox setup cost and communication cost
- Two special cases
  - Facility location problem
    - Single middlebox placement
  - Generalized assignment problem
    - Each middlebox has a limited processing volume
    - Placing middleboxes and assigning to flows

[4] Near Optimal Placement of Virtual Network Functions (INFOCOM '15)

A Service Chain Model [2]

- Objective
  - Minimizing the total bandwidth consumption
- Solutions
  - Consider traffic-changing effects
  - Place middleboxes for a single flow

$\boxed{m_1}\quad\boxed{m_2}\quad\boxed{m_3}$

Non-ordered

(Optimal greedy: sort traffic-changing ratios in increasing order)

$\boxed{m_1}\rightarrow\boxed{m_2}\rightarrow\boxed{m_3}$

Totally-ordered

(Optimal DP: latter middleboxes must be after front ones)

$\boxed{m_1}\quad\boxed{m_2}\rightarrow\boxed{m_3}$

Partially-ordered

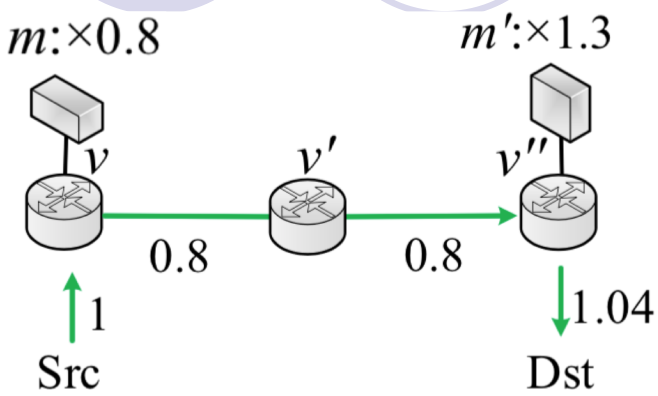
(NP-hard: reduced from the Clique Problem)

[2] Traffic Aware Placement of Interdependent NFV Middleboxes (INFOCOM '17)

2. Our Model

- Problem
  - Placing middleboxes to satisfy all flows' network service requests
- Network service requests
  - Multiple middleboxes
    - Middlebox set with or without dependency relations
- Cost
  - Middlebox setup
    - Sum of middlebox setup cost
  - Bandwidth consumption
    - Sum of each flow's bandwidth consumption cost on each link
- Objective
  - Minimizing total cost of middlebox setup and bandwidth consumption

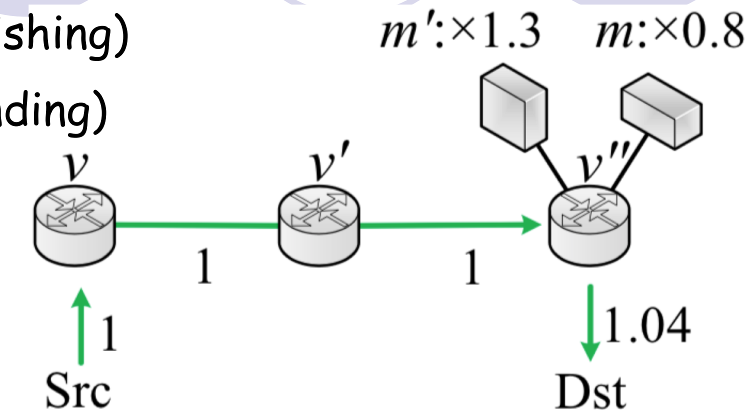
A Motivating Example



Independent middleboxes

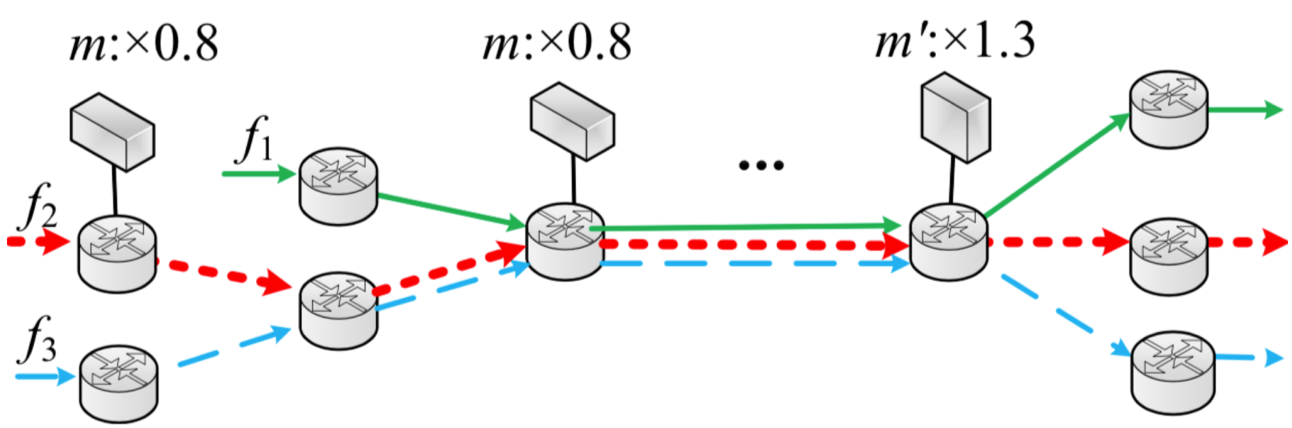
m: 0.8 (diminishing)

m': 1.3 (expanding)



Dependent middleboxes: m' before m

Red flow with high rate



A flow covered by multiple middleboxes

(Multiple coverage: when additional setup cost is less than the reduced bandwidth consumption cost)

3. Problem Formulation

- Middlebox setup cost
  - $$c_1 = \sum_{m \in M} \sum_{v \in V} c_m$$
    - c_m: unit setup cost of middlebox m
- Bandwidth consumption cost
  - $$c_2 = \sum_{f \in F} \sum_{e \in p_f} w(b_f^e)$$
    - $w(b_f^e)$: bandwidth cost function of flow f on link e
  - $$b_f^e = r_f \prod_m \lambda_m$$
    - r_f: initial traffic rate of flow f
    - λ_m : traffic-changing ratio of middlebox m
- Objective
  - Minimizing c_1+c_2

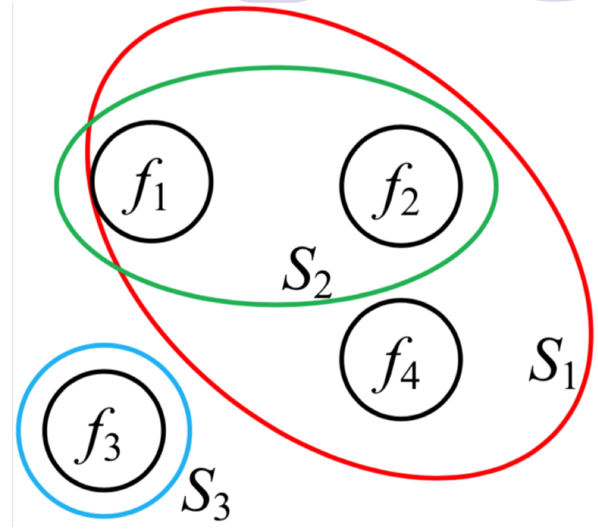
Problem Formulation (cont'd)

- Translog bandwidth cost function on each link

$$w(b_f^e) = \log(b_f^e) = \log(r_f \prod \lambda_m) = \log(r_f) + \sum \log(\lambda_m)$$

- Reasons
  - Widely used in Cisco EIGRP and OSPF protocols
  - Log-linear for easy calculation
- The weight of setup cost and bandwidth consumption
  - Adjusting the traffic-changing ratios and unit setup costs of middleboxes

Problem Complexity



NP-hard

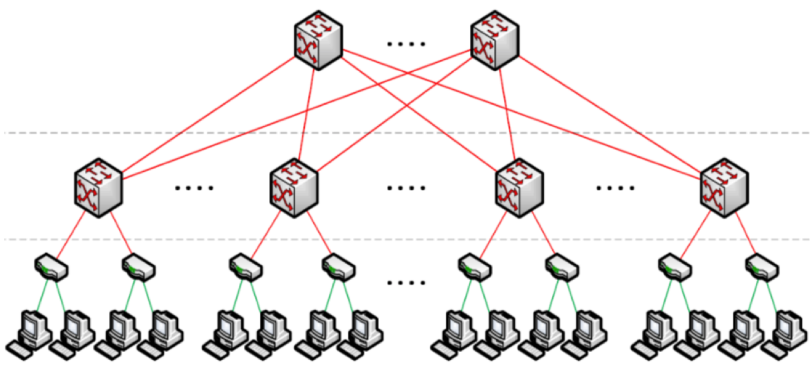
- Even with no traffic-changing effects
- Even when placing a single middlebox

Proof

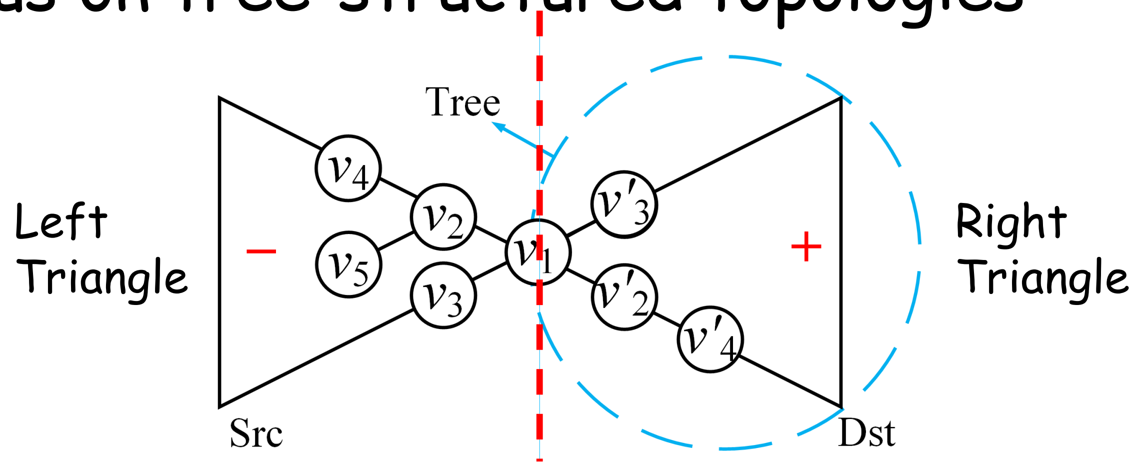
- Reduction from set-cover problem
- Use minimum number of middleboxes to "cover" all flows
  - Flows as elements: $F= \{f_1,f_2,\ldots, f_{|F|}\}$
  - Placed middleboxes as sets: $\{S_1, S_2,\ldots\}$
  - $S_1=\{f_1, f_2, f_4\}$, $S_2=\{f_1, f_2\}$, $S_3=\{f_3\}$

Problem Complexity (cont'd)

- In this paper, we focus on tree-structured topologies

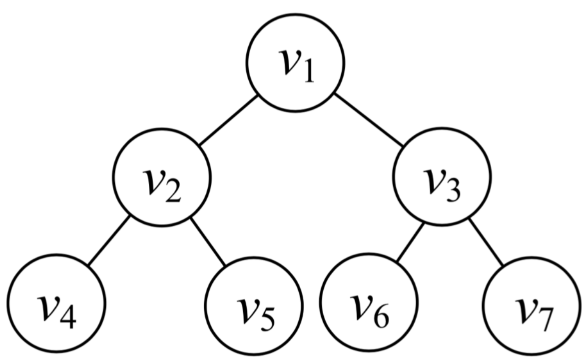


Tree-based data centers

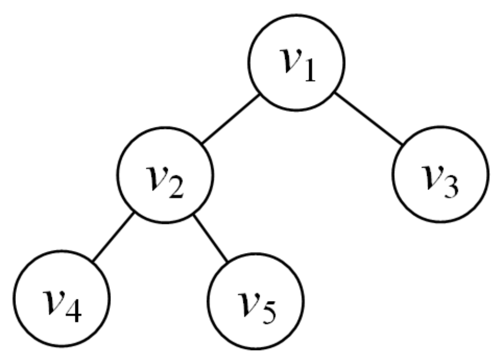


Hierarchical data centers

Each triangle is mostly a perfect or complete tree



Perfect tree



Complete tree

4. Placing a Single Middlebox

Solution

- Local Greedy Algorithm (LGA)

Steps

- Calculate each total cost of placing middleboxes in a whole level
- Select the level with the minimum total cost
- Iterative implementation
  - From top level to bottom, total costs will decrease and then increase
  - Select the level with the local minimum

4. Placing a Single Middlebox (cont'd)

Time complexity (|V|: #node)

- O(|V|)

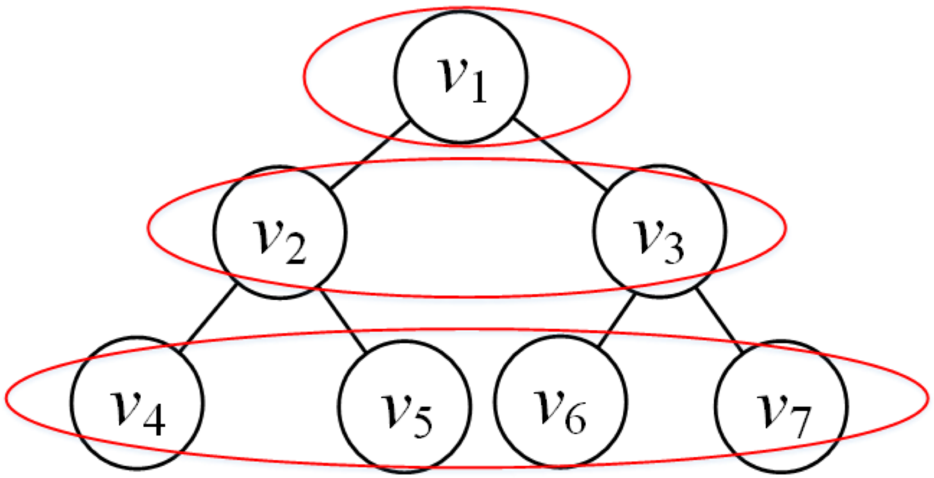
Optimal for perfect tree topologies

- Symmetry of placement
- No multiple "coverage" situation

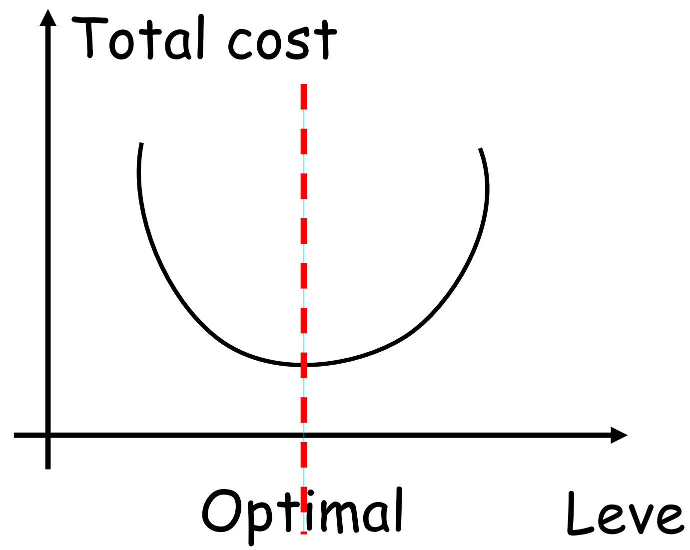
Also optimal for complete tree topologies

- Also multiple "coverage" situation
- The most unbalanced traffic distribution: left and right subtrees of root have a depth difference of 1

Illustration



Calculate level by level



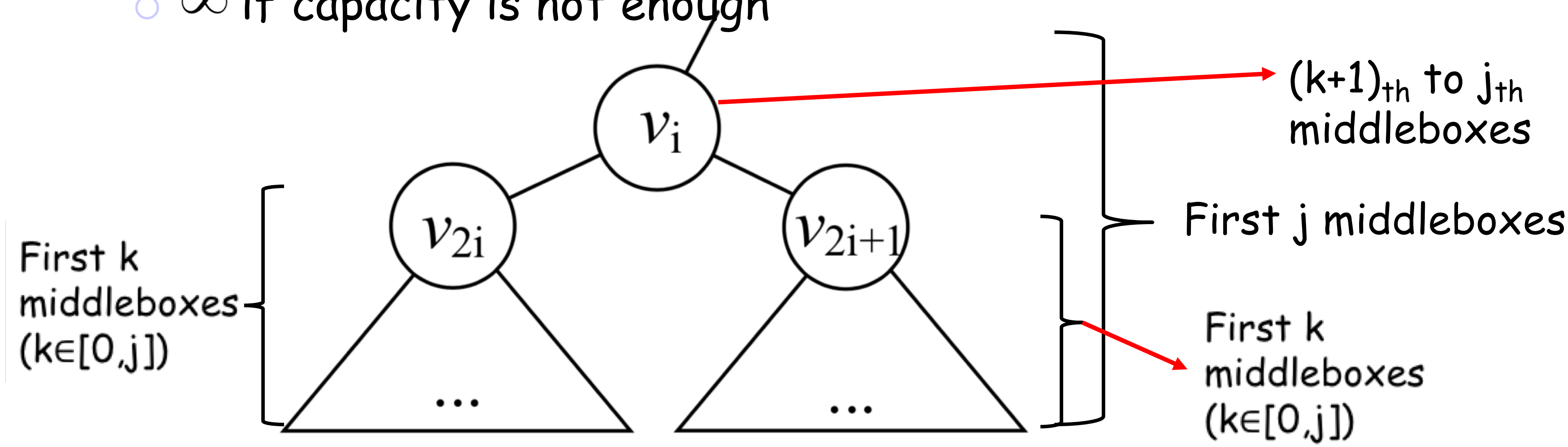
5. Placing Multiple Middleboxes

Non-ordered middlebox set placement

- Solution
  - Combined Local Greedy Algorithm (CLGA)
- Insight
  - Place each middlebox independently by applying LGA
- Time complexity (|V|: #node, |M|: #middlebox)
  - $O(|V||M|)$
- Optimal for complete trees

Totally-ordered Middlebox Set Placement

- Solution: Dynamic Programming (DP)
- Works for infinite and finite vertex capacity
- OPT(i, j)
  - Minimum cost of subtree with root v_i when placing first j middleboxes in the set
  - ∞ if capacity is not enough



Dynamic Programming Formulation

- Left triangle

$$
\mathrm{OPT}(i,j) = \begin{cases} \min\limits_{0 \le k \le j} \{\mathrm{OPT}(2i,k) + \mathrm{OPT}(2i+1,k) & \\ + \sum\limits_{k<l\le j} c_l + \lfloor \log i \rfloor \sum\limits_{k<l\le j} \lambda_l\}, & 1 \le i \le \lfloor \frac{n}{2} \rfloor. \\ \sum\limits_{0\le l\le j} c_l + \lfloor \log i \rfloor r_f, & \lfloor \frac{n}{2} \rfloor < i \le n. \\ \infty & \text{if not enough node capacity.} \\ 0 & \text{otherwise.} \end{cases}
$$

Left subtree

Right subtree

Bandwidth consumption

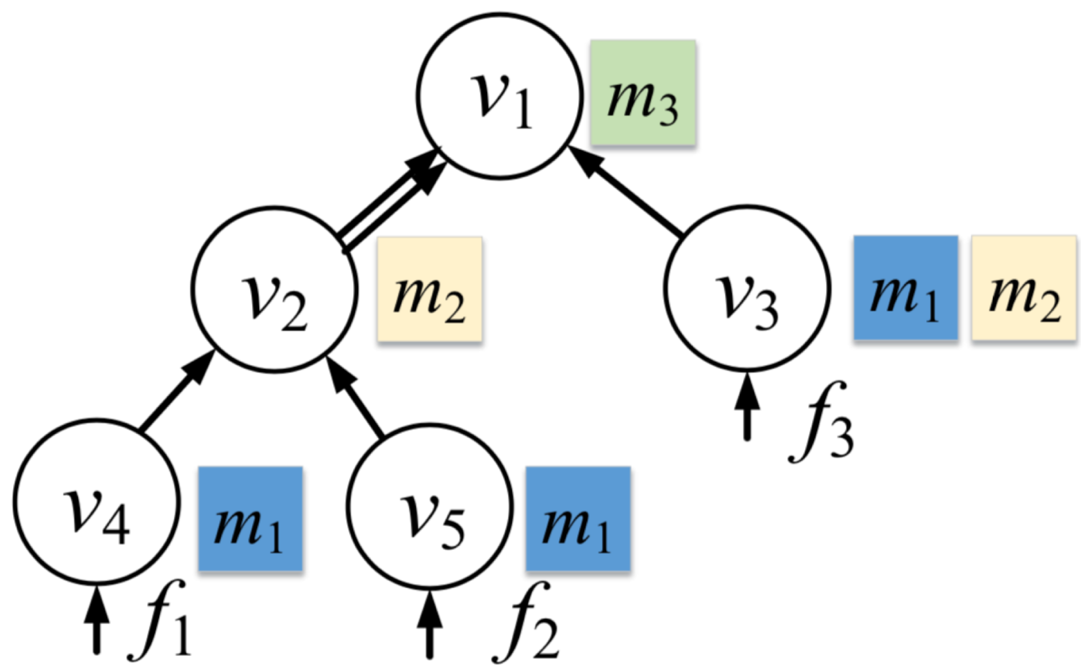
Newly placed middleboxes

- Right triangle
  - Similar to the left triangle's formulation

An Example

	m_1	m_2	m_3
Traffic-changing ratio	0.5	0.8	1.1
Setup cost	0.2	0.4	0.3

- Dependency relations
  - m_1->m_2->m_3
- Initial traffic rate
  - r_1=r_2=r_3=1



Totally-ordered Middlebox Set Placement (cont'd)

Insights

- The optimal placement with root v_i by placing first j and its two subtrees by placing no more than j middleboxes

Perfect tree

- Transformed to a line
- Similar to a single flow placement

Complete tree

- No multiple "coverage" situation

Time complexity (|V|: #node, |M|:#middlebox)

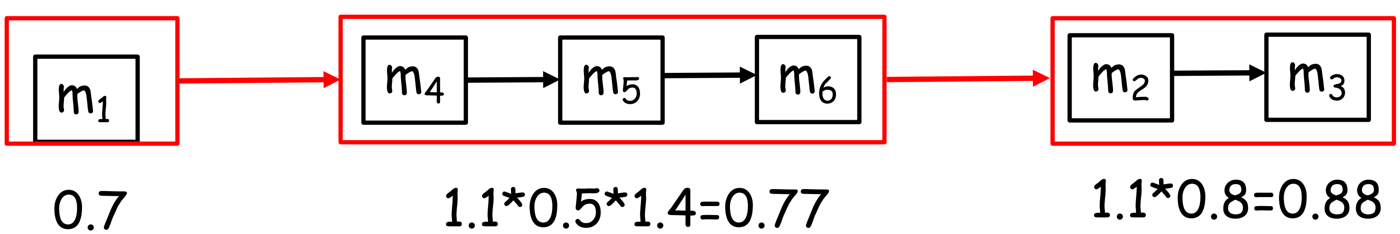
- $O(|V||M|^3)$

Partially-ordered Middlebox Set Placement

- NP-hard even for a single flow [2]
- One heuristic solution
  - Insight
    - Transform into a totally-ordered middlebox set
  - Steps (λ: traffic-changing ratio)
    - Treat middleboxes with dependencies as a single middlebox
    - Sort middleboxes in increasing order of λ
  - Example
    - Middlebox set

	m_1	m_2	m_3	m_4	m_5	m_6
λ	0.7	1.1	0.8	1.1	0.5	1.4

    - Dependency relationship: $m_2 \rightarrow m_3$, $m_4 \rightarrow m_5 \rightarrow m_6$



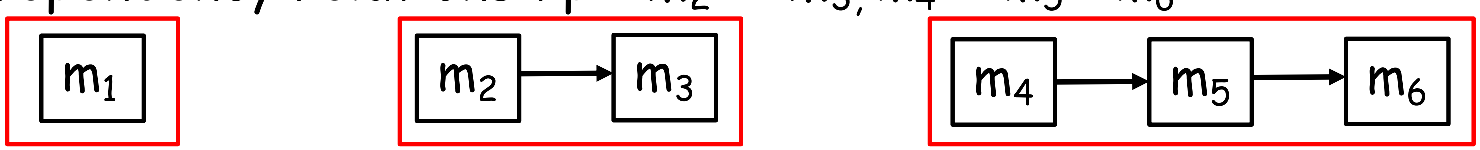
[2] Traffic aware placement of interdependent NFV middleboxes (INFOCOM '17)

Partially-ordered Middlebox Set Placement (cont'd)

- Another heuristic solution
  - Insight
    - Transform into a non-ordered middlebox set
  - Steps
    - Treat middleboxes with dependencies as a single middlebox by a topological order
    - No dependency relations among new middleboxes
  - Example
    - Middlebox set

	m_1	m_2	m_3	m_4	m_5	m_6
λ	0.7	1.1	0.8	1.1	0.5	1.4

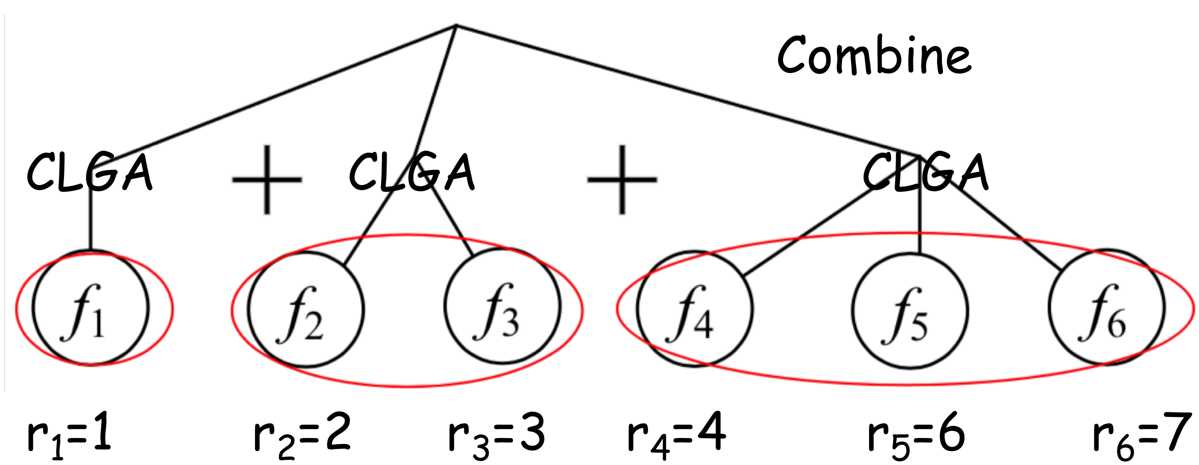
    - Dependency relationship: $m_2 \to m_3$, $m_4 \to m_5 \to m_6$



0.7   1.1*0.8=0.88   1.1*0.5*1.4=0.77

6. Handling Heterogeneous flows for Non-ordered Middlebox Set

- Group Flows by Initial Bandwidths (GFIB)
  - Group flows by initial traffic rates (r_f: f's traffic rate)
    - #group: $\lfloor \log_2 \frac{\max r_f}{\min r_f} \rfloor + 1$
    - The traffic rate range of the i^th group: $2^{i-1} \times \min r_f \le r_f < 2^i \times \min r_f$
  - Treat flows in each group as homogeneous
  - Apply CLGA for each group
- An example



max r_f= 7
min r_f= 1
Group 1: [1,2)
Group 2: [2,4)
Group 3: [4,8)

6. Handling Heterogeneous Flows for Non-ordered Middlebox Set (cont'd)

- Time complexity

$$\max\{O(|V|\log|V|),O(|V|(\left\lfloor \log_2 \frac{\max r_f}{\min r_f} \right\rfloor + 1))\}$$

- Performance-guaranteed algorithm
  - Approximation ratio [5]: $\left\lfloor \log_2 \frac{\max r_f}{\min r_f} \right\rfloor + 1$

[5] On Optimal Scheduling of Multiple Mobile Chargers in Wireless Sensor Networks (MSCC '14)

7. Simulation

- Our algorithms
  - LGA
    - Single middlebox
    - Select the level with the minimum cost
  - CLGA
    - Non-ordered middlebox set
    - Apply LGA independently
  - DP
    - Totally-ordered middlebox set
    - Dynamic programming
  - GFIB
    - Heterogeneous flows
    - Group flows by initial traffic rates
    - Combine placement by applying CLGA for each group

7. Simulation

- Comparison algorithms
  - Random-fit
    - Randomly place middleboxes until all flows are satisfied
  - NOSP [2]
    - Place middleboxes in increasing order of traffic-changing effects for each flow from source to destination independently
    - For single middlebox or non-ordered middlebox set
  - TOSP [2]
    - Dynamic programming based algorithm for each flow independently
    - For totally-ordered middlebox set with or without vertex capacity

[2] Traffic aware placement of interdependent NFV middleboxes (INFOCOM '17)

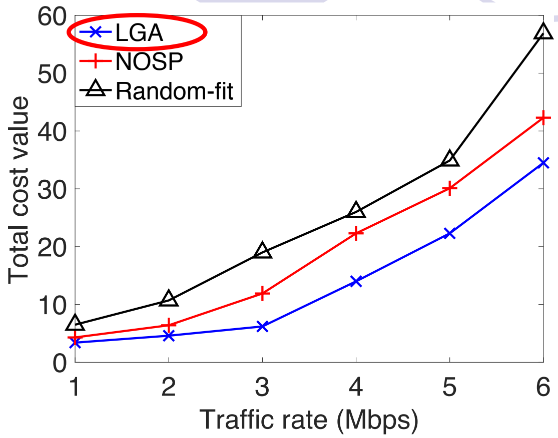
Settings

- Topology
  - Perfect 5-layer binary tree for each triangle
- Facebook data center traffic trace
  - Single-flow initial traffic rate: 1~6 Mb
- Middlebox set

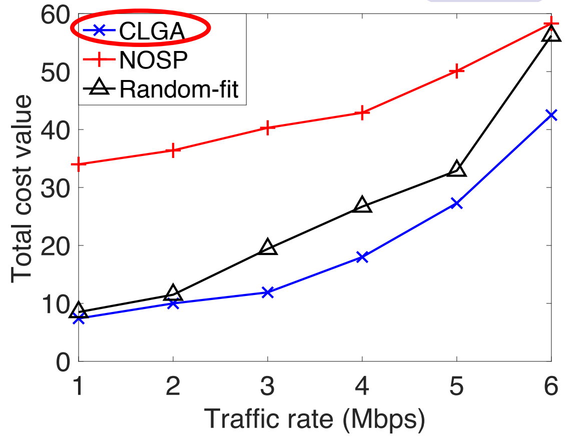
	m_1	m_2	m_3	m_4
Traffic-changing ratio	0.7	0.8	1.1	1.2
Setup cost	0.4	0.6	0.2	0.8

- Dependency relationship
  - m_2 -> m_3 -> m_1 -> m_4

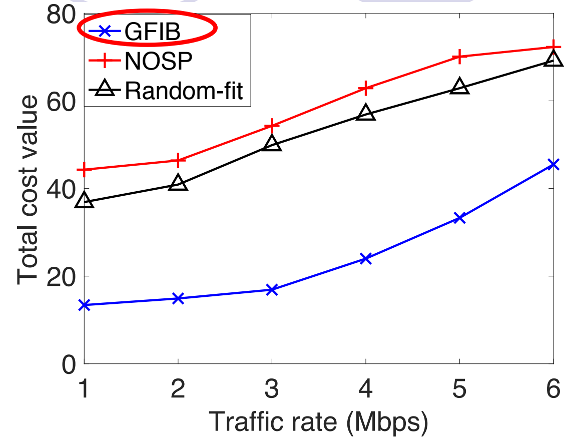
Simulation Results



Single middlebox (LGA)



Non-ordered middlebox set (CLGA)

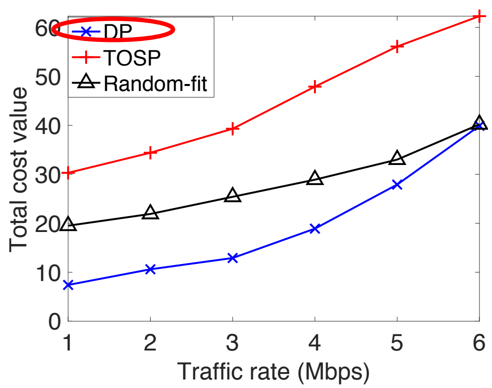


Bandwidth heterogeneity (GFIB)

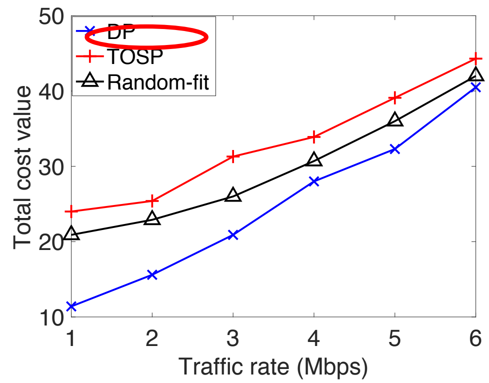
- LGA costs 20.3% less than NOSP and 35.1% less than Random-fit.
- CLGA performs the best even with heavy traffic.
- The performance of Random-fit is not steady.
- For heterogeneous flows, GFIB saves about 36.9% and 34.0% compared to NOSP and Random-fit.

Simulation Results (cont'd)

Totally-ordered middlebox set



Without vertex capacity



With vertex capacity

Totally-ordered middleboxes	Total cost	Set-up cost
$m_2 \to m_3 \to m_1 \to m_4$	20.9	10.4
$m_3 \to m_1 \to m_2 \to m_4$	23.7	12.0
$m_1 \to m_4 \to m_3 \to m_2$	22.8	9.6
$m_1 \to m_2 \to m_3 \to m_4$	11.9	4.4
$m_4 \to m_3 \to m_2 \to m_1$	24.7	10.2

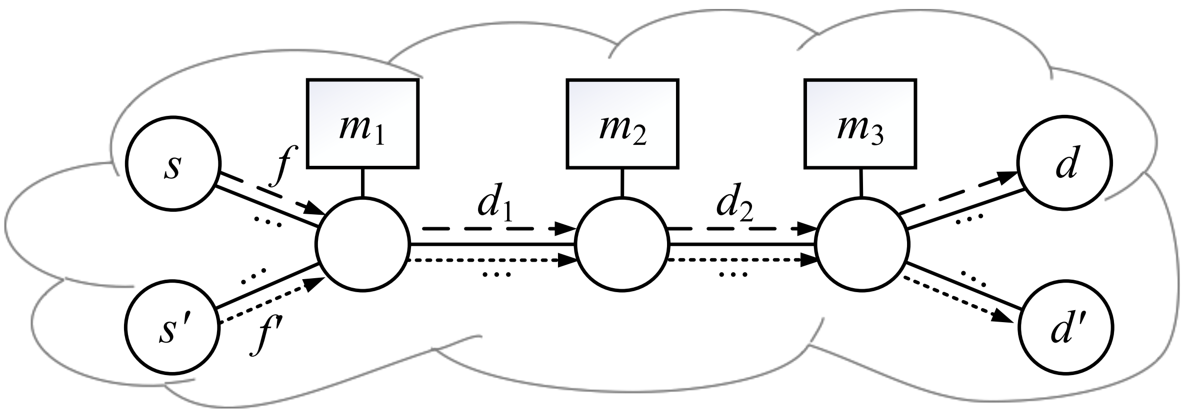
Middlebox order effect at 3 Mbps (DP)

- The total cost is larger than the non-ordered middlebox set.
- Limited vertex capacity increases the minimum cost.
- The order of a middlebox set matters not only for total cost but also for set-up cost.

8. Conclusion and Future Work

- Middlebox constraints
  - Traffic-changing effects
  - Dependency relations
  - Flow sharing
- Middlebox placement
  - Balancing middlebox set-up cost and bandwidth consumption
- Tree-structured topologies
  - Optimal algorithms for homogeneous flows
  - Performance-guaranteed algorithm for heterogeneous flows
- Future work
  - General tree-structures

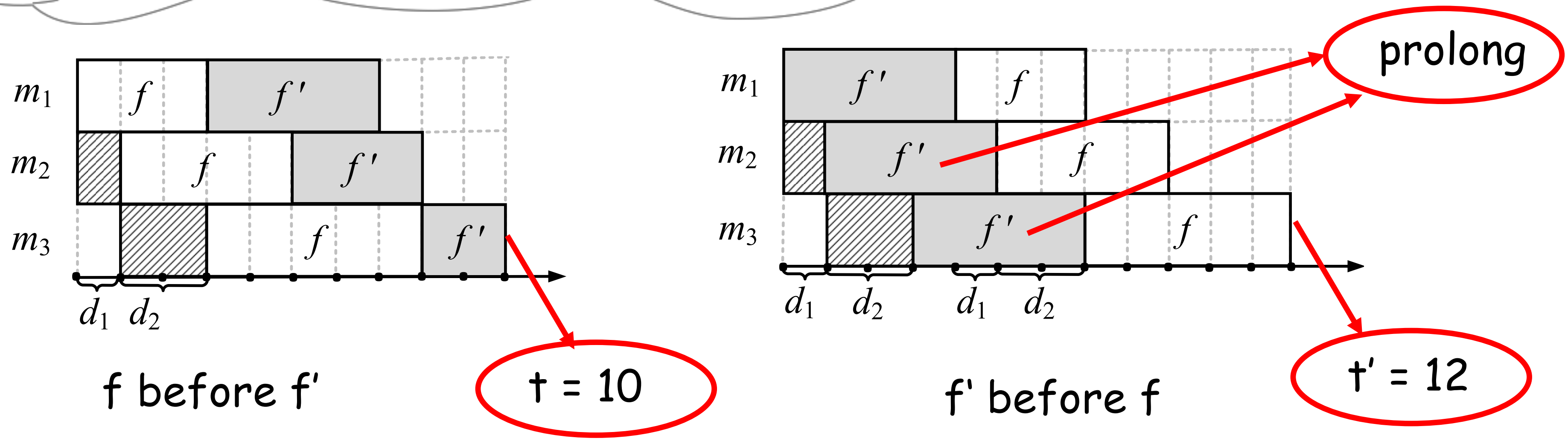
Other Service Chain Models



$d_1 = 1$ $d_2 = 2$

Processing time

Middleboxes / Flows	m_1	m_2	m_3
f	3	4	5
f'	4	3	2



- Minimizing the makespan
- Minimizing the average completion time

Q & A