Joint Composition, Routing, and NF Placement for NFV-enabled Multicast Services

PhD Thesis

Omar Alhussein

Supervisor: Weihua Zhuang
Department of Electrical and Computer Engineering
University of Waterloo

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Outline

Introduction

System model

Routing and NF placement

Admission mechanism and online framework

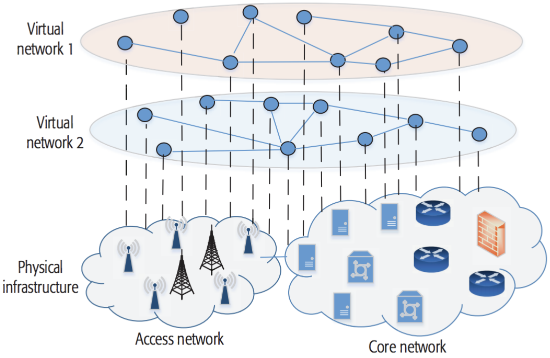
Model-free dynamic provisioning mechanism

Conclusions

Next-generation Networks

- 5G vision cannot be realized by a *one-size-fits-all* network architecture
- The current approach is to provide a virtually layered and software defined network architecture, using NFV and SDN

- Software-defined Networking (SDN)
  - Decouple the data plane from the control plan → allows for centralized algorithms and approaches
- Network function virtualization (NFV)
  - Softwarize and virtualize NFs to run on commodity servers on-demand

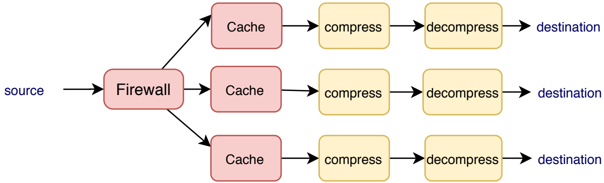


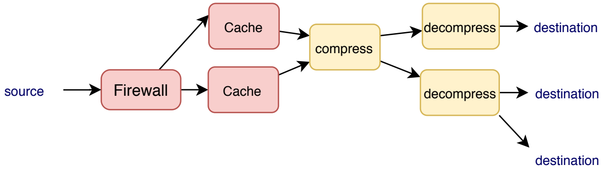
Network virtualization [1]

[1] N. Zhang, P. Yang, S. Zhang, D. Chen, W. Zhuang, B. Liang, and X. S. Shen, "Software Defined Networking Enabled Wireless Network Virtualization: Challenges and Solutions," IEEE Netw., vol. 31, no. 5, pp. 42–49, 2017.

Network Service - Definition

- Network service:
  - Traditional connectivity between terminals
  - Network application (network policy)
- Example:
  - Multicast firewall-protected web-based traffic dissemination service
- NF chain is *one* realization of a network service
- NF chain can have best-effort NFs





Research Objectives

PhD research

Routing and NF placement

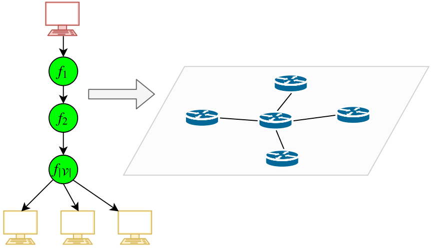
How to route the traffic and place the NFs?

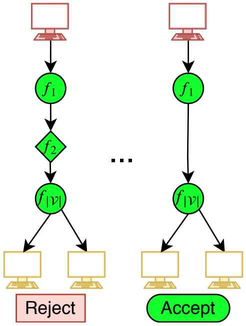
Admission mechanism and online strategy

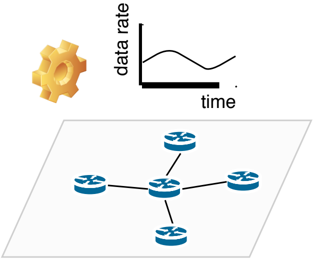
How to deal with multiple services in an online manner?

Model-free dynamic provisioning

How to dynamically allocate resources based on time-varying traffic?







Outline

Network Functions and Service Requests

- NFs can be deployed on commodity servers (NFV nodes) as demanded
- Examples include firewall, intrusion detection, Web cache, proxy, and service gateway

- The rth service request is expressed as

$$S^r = (s^r, \mathcal{D}^r, \mathcal{V}^r, d^r), \qquad S^r \in \sigma$$

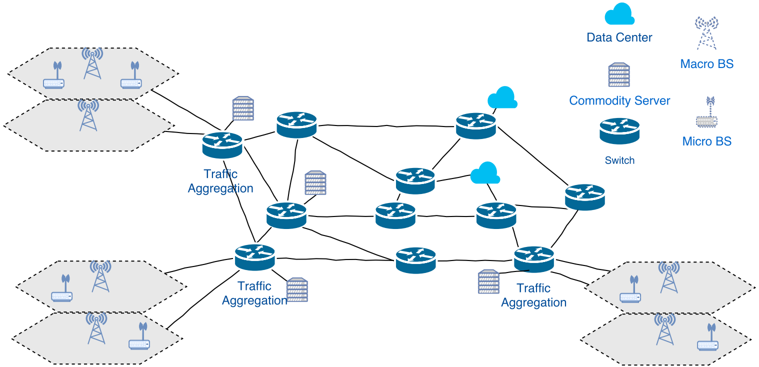
- Source node
- Destination nodes
- Required transmission rate (packet/s)
- Set of NFs to be traversed in order
- Required processing rate for each NF (packet/s)

- s^r
- $\mathcal{D}^r$
- d^r
- $\mathcal{V}^r = \{f_1^r, f_2^r, \ldots, f_{|\mathcal{V}^r|}^r\}$
- $C(f_i^r)$

Network Substrate

$$\mathcal{G} = (\mathcal{N}, \mathcal{L})$$

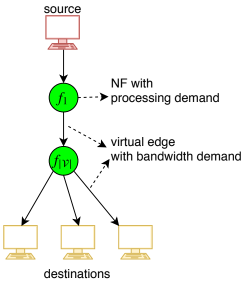
- $\mathcal{N}$ and $\mathcal{L}$ are the sets of nodes and links, respectively
- Residual transmission resource, $B(l)$ packet/s, $l \in \mathcal{L}$
- Residual processing resource, $C(n)$ packet/s, $n \in \mathcal{N}$

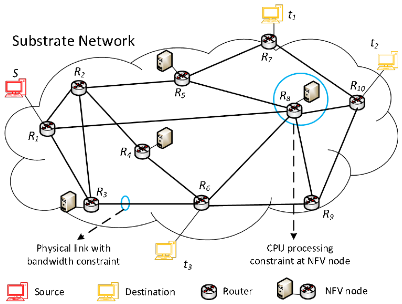


Outline

Joint Routing and NF Placement for Multicast Services

- Input:
  - Network substrate $\mathcal{G} = (\mathcal{N}, \mathcal{L})$
  - Multicast NF chains $S^r = (s^r, \mathcal{D}^r, f_1^r, f_2^r, \ldots, f_{|\mathcal{V}|}^r, d^r)$, $S^r \in \mathcal{R}$
- Output:
  - Embedded multicast topology for each NF chain on the network substrate
- Description:
  - How to jointly embed the multicast services and route traffic between source and destinations through a chain of NFV nodes to minimize the network provisioning cost





Motivations

Resources balance

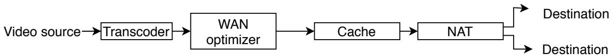
A minimal feasible number of NF instances can lead to large link provisioning cost (and vice versa)

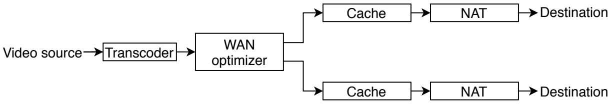
- Need to strike a balance between processing and transmission resources

Flexible design considerations

Multicast replication points should *not* be limited as a result of placement of NFs
Need to incorporate multipath routing

- Crucial for geo-distributed environments
- Existing works perform NF placement first, followed by multicast routing
  - Results in simple adapted algorithms, but with less flexibility in service topology customization





ILP Formulation

- Formulate an ILP for single-service scenario with multipath routing:
  - Model a service as a composition of multiple multicast trees that pass by identical NF instances

- Minimize transmission and processing costs

$$\min \sum_{r\in\mathcal{R}} \sum_{l\in\mathcal{L}} \sum_{j\in\mathcal{S}_1^J} \sum_{i=0}^{|\mathcal{V}^r|} \alpha \left(\frac{r_{lij}^r}{B(l)} + x_{lij}^r \right) + \boxed{\sum_{r\in\mathcal{R}} \sum_{i=1}^{|\mathcal{V}^r|} \sum_{n\in\mathcal{N}} \beta \frac{C(f_i^r)}{C(n)} z_{ni}^r}$$

subject to :

- Multicast routing constraints (w/ multipath)

$$\sum_{(n,m)\in\mathcal{L}} y_{(n,m)it}^j - \sum_{(m,n)\in\mathcal{L}} y_{(m,n)it}^j = \pi^j \left(u_{n(i+1)t} - u_{nit}\right)$$

- Transmission and processing constraints

$$\sum_{j=1}^{J} \sum_{i=0}^{|\mathcal{V}|} r_{li}^j \leq B(l),\ l \in \mathcal{L}.$$

$$\sum_{i=1}^{|\mathcal{V}|} z_{ni} C(f_i) \leq C(n),\ \forall n \in \mathcal{M}$$

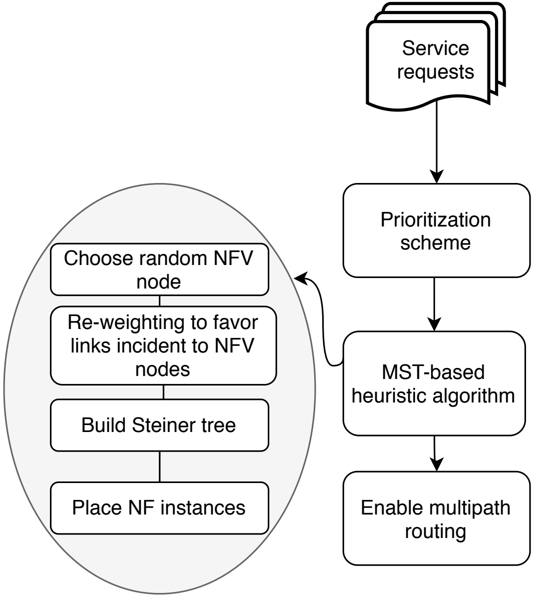
- Data rate requirement

$$\sum_{j=1}^{J} d_r^j = \bar{d}_r$$

Heuristic algorithm

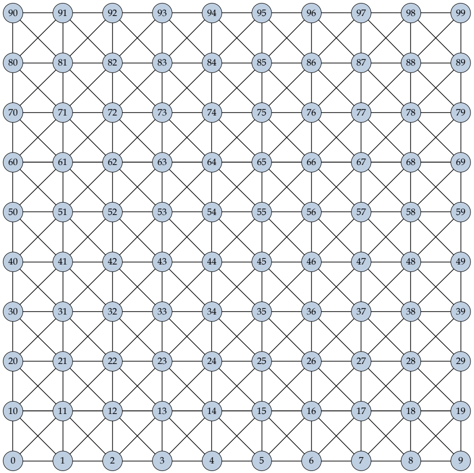
- Low-complexity, modular and flexible framework:

1. Prioritize services that
   - maximize overall throughput and minimize provisioning cost
2. Embed each request using MST-based algorithm:
   - Enables one-to-many and many-to-one mapping
   - Flexibility for placing multicast replication
3. Enable multipath routing:
   - Needed for geo-distributed environments



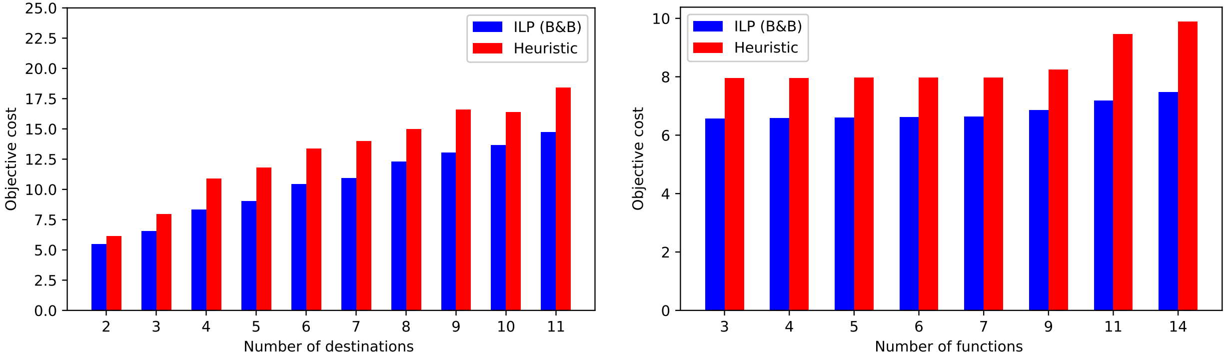
Performance Evaluation

- Simulated network substrate
  - $|\mathcal{N}| = 100, |\mathcal{L}| = 684$
  - 25% selected NFV nodes
  - processing and transmission $\sim \mathcal{U}(50, 200)$
- Varying multicast requests



Performance Evaluation

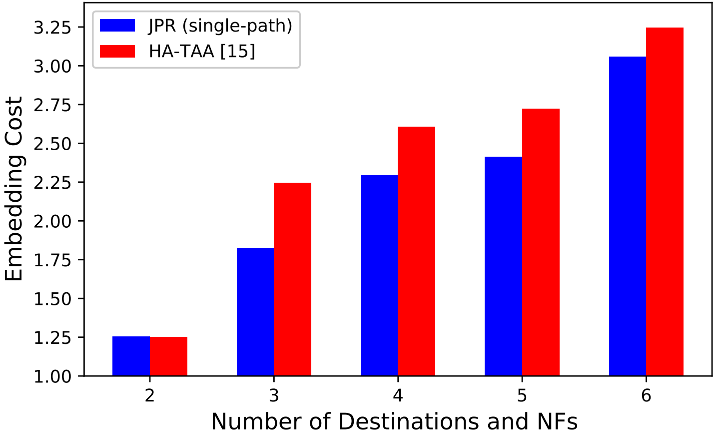
- To corraborate performance of algorithm:
  - Compare ILP and heuristic performance as $|\mathcal{N}|$ and $|\mathcal{D}|$ grows



(A) (B)

Performance Evaluation

- Comparison between proposed heuristic algorithm and heuristic (HA-TAA) in [15]
    - HA-TAA does not have flexible design considerations



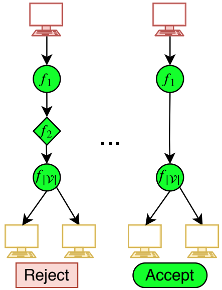
(b)

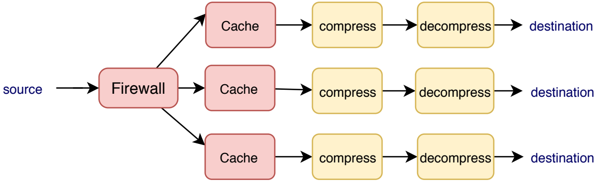
- [15] S. Q. Zhang, A. Tizghadam, B. Park, H. Bannazadeh, and A. Leon-Garcia, "Joint NFV placement and routing for multicast service on SDN," in Proc. IEEE NOMS, 2016, pp. 333–341.

Outline

Admission Mechanism and Online Framework

- Input:
  - Network substrate $\mathcal{G} = (\mathcal{N}, \mathcal{L})$
  - Online sequence of unicast and multicast service requests $\sigma = (S^1, S^2, \dots)$
  - NFs can be best-effort and mandatory
- Output:
  - Embedded multicast topology for accepted NF chains on the network substrate
- Description:
  - To design an admission mechanism and an online strategy for NFV-enabled requests to maximize the amortized throughput while taking into account the type of service and heterogeneity of NFs





Motivations

Problem nature and design requirements

Requests arrive in an online and random manner;
Need to develop an online algorithm that incorporates both multicast and unicast services with mandatory and best-effort NFs

- Provide an online treatment with competitive analysis
- Existing online algorithms in NFV-enabled literature:
  - consider one resource type, or one NF types
  - admission mechanism and functions are not well-justified
- We develop a generalized primal-dual online framework that provides direct and general analysis:
  - all-or-something scheme for unicast/multicast services
  - Competitive performance is direct and more general
  - Functions and conditions are well-justified, and offer many possibilities for extensions
  - Provide one-step approximation algorithm for routing and placement in the unconstrained scenario

Offline Formulation and Online Treatment

- Balanced and modular profit functions:
  - $\varrho^r = d^r|\mathcal{D}^r|^k$ and $\rho^r = \eta^r C(f^r)$

$$\min \sum_{l\in\mathcal{L}} B(l)\boxed{\bar{x}(l)} + \sum_{n\in\mathcal{N}} C(n)\boxed{\tilde{x}(n)} + \sum_{S^r\in\sigma} z^r \quad (1a)$$

(Primal) subject to :

$$\forall S^r \in \sigma, P \in \mathcal{P}(r) : \sum_{l\in P\cap\mathcal{L}} d^r\bar{x}(l) + z^r \geq \alpha\varrho^r \quad (1b)$$

$$\forall S^r \in \sigma, P \in \mathcal{P}(r) : \sum_{n\in P\cap\mathcal{N}} \tilde{x}(n) + z^r \geq \beta\rho^r \quad (1c)$$

$$\forall S^r \in \sigma, l \in \mathcal{L}, n \in \mathcal{N} : z^r, \bar{x}(l), \tilde{x}(n) \geq 0. \quad (1d)$$

$$\max \alpha \sum_{S^r\in\sigma} \sum_{P\in\mathcal{P}(r)} \varrho^r y_P^r + \beta \sum_{S^r\in\sigma} \sum_{P\in\mathcal{P}(r)} \rho^r y_P^r \quad (2a)$$

(Dual) subject to :

$$\forall S^r \in \sigma : \sum_{P\in\mathcal{P}(r)} y_P^r \leq 1 \quad (2b)$$

$$\forall l \in \mathcal{L} : \sum_{S^r\in\sigma} \sum_{P\in\mathcal{P}(r)|l\in P} d^r y_P^r \leq B(l) \quad (2c)$$

$$\forall n \in \mathcal{N} : \sum_{S^r\in\sigma} \sum_{P\in\mathcal{P}(r)|n\in P} C(f^r) y_P^r \leq C(n) \quad (2d)$$

$$\forall S^r \in \sigma, P \in \mathcal{P}(r) : y_P^r \geq 0. \quad (2e)$$

- Online algorithm: Find link/node cost funcs $(\bar{x}(l), \tilde{x}(n))$ s.t. $\overbrace{\frac{\partial J}{\partial y_P^r}}^{\textit{change in primal}} \leq 2\xi \overbrace{\frac{\partial A}{\partial y_P^r}}^{\textit{change in dual}}$ while maintaining constraints of primal and dual satisfied

Online Algorithm

1. Admission mechanism (accept, reject, partial accept)

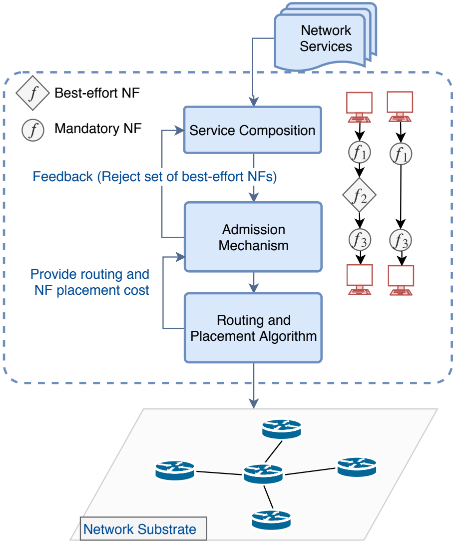
$$\sum_{l \in P \cap \mathcal{L}} d^r \bar{x}^{r-1}(l) \leq \alpha \varrho^r \text{ and } \sum_{n \in P \cap \mathcal{N}} C(f^r) \tilde{x}^{r-1}(n) \leq \beta \rho^r$$

2. Dynamic cost functions (that change after each request arrival)

$$\bar{x}^r(l) = \bar{x}^{r-1}(l) e^{\varphi \frac{d^r}{B(l)}} + \frac{1}{L}(e^{\varphi \frac{d^r}{B(l)}} - 1)$$

$$\tilde{x}^r(n) = \tilde{x}^{r-1}(n) e^{\phi \frac{C(f^r)}{C(n)}} + \frac{1}{K}(e^{\phi \frac{C(f^r)}{C(n)}} - 1)$$

3. One-step approximation algorithm for the routing and NF placement problem for unconstrained scenario using multilayer transformation



Main Result

Theorem

The competitive performance of the joint admission mechanism and the online routing and NF placement framework is

$$\mathcal{O}(\max(\varphi, \phi))$$

where $d^r \leq \frac{\min_{l \in \mathcal{L}} B(l)}{\varphi}$, $C(f^r) \leq \frac{\min_{n \in \mathcal{N}} C(n)}{\phi}$, $\varphi \geq \ln(2\alpha L|\mathcal{D}|^k_{\max} + 2)$, and $\phi \geq \ln(2\beta K \frac{\eta_{\max}}{\eta_{\min}} + 2)$.

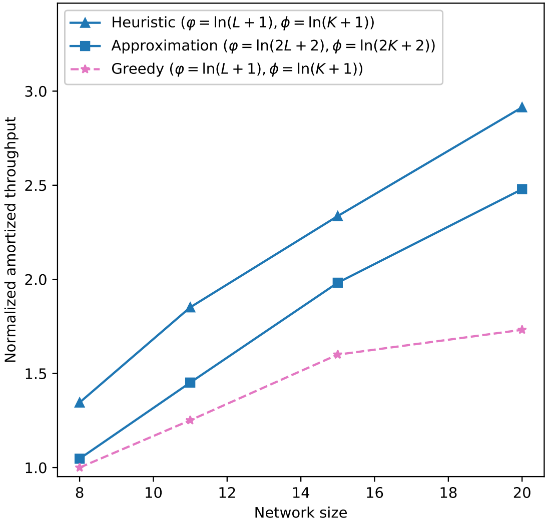
- Competitive performance
  - is logarithmic in $\overbrace{L}^{\max \#\text{hops}}$, $\overbrace{K}^{\max \#\text{NFs}}$, $\overbrace{|\mathcal{D}|^k_{max}}^{\max \#\text{desinations}}$, and $\overbrace{\frac{\eta_{\max}}{\eta_{\min}}}^{\max \text{incentive}}$
  - Tunable tradeoff between fairness and optimality concerning type of service (unicast vs. multicast)
  - Tunable tradeoff between variability of incentive and optimality concerning heterogeneity of NFs

Performance Analysis

- Approximation algorithm (with $\phi \geq \ln(2\beta K \frac{\eta_{\max}}{\eta_{\min}} + 2)$ and $\varphi \geq \ln(2\alpha L|\mathcal{D}|^{k}_{\max} + 2)$)
- Heuristic algorithm: Similar to approximation algorithm
  - with new weights $\varphi \geq \ln(\alpha L|\mathcal{D}|^{k}_{\max} + 1)$ and $\phi \geq \ln(\beta K \frac{\eta_{\max}}{\eta_{\min}} + 1)$
  - with performing extra step of checking against resource violations
- Greedy algorithm:
  - Accept as long as there is enough resources (no admission mechanism)
- Tests are performed over random and real network substrate topologies

Performance Analysis

- Testing throughput as size of network grows



- Linear network substrate
- Unicast service requests
- We fix $L = K = 4$

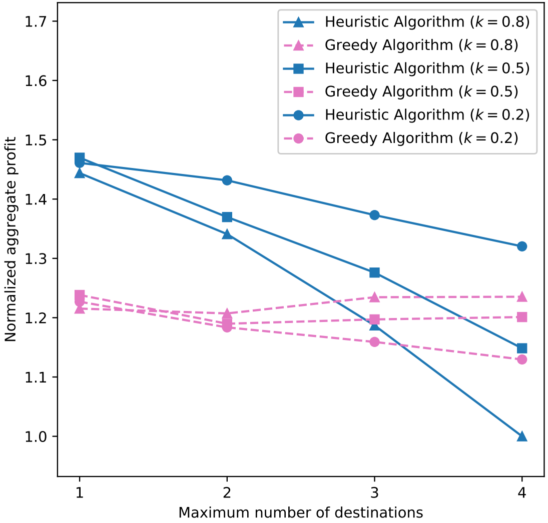
- Heuristic outperforms approximation by 30% ($\ln(2L)$)
- Approximation outperforms greedy
  - shows improvement due to admission mechanism
- As network size grows, L becomes more competitive compared to network size

Performance Analysis

- Tradeoff between fairness/variability and optimality

- Random (Barbasi-Albert) network substrate
- Multicast service requests
- $K = 4$
- L is set to the maximum hop distance between any pair of nodes

- As $|\mathcal{D}|^k_{\max}$ increases, competitive performance of heuristic and approximation algorithms decrease



Outline

Model-free Dynamic Provisioning for NFV-enabled Services

- Input:
  - Network substrate $\mathcal{G} = (\mathcal{V}, \mathcal{L})$ with time-varying resources
  - $S = (s, t, \mathcal{V}, d(\tau))$ with time-varying data rate and processing requirements

- Output:
  - Dynamic topology on the network substrate

- Description: Given a service request with time-varying data rate requirement, how to develop a dynamic provisioning method to minimize the function, link, and routing provisioning costs

Motivations

Problem nature

NFV-enabled services exhibits time-varying demand
Traffic need not be periodic nor tractable

- A static solution renders either under- or over-utilized solution
- Optimization-based place strong assumptions on the traffic model
- Opt for model-free approach using deep reinforcement learning

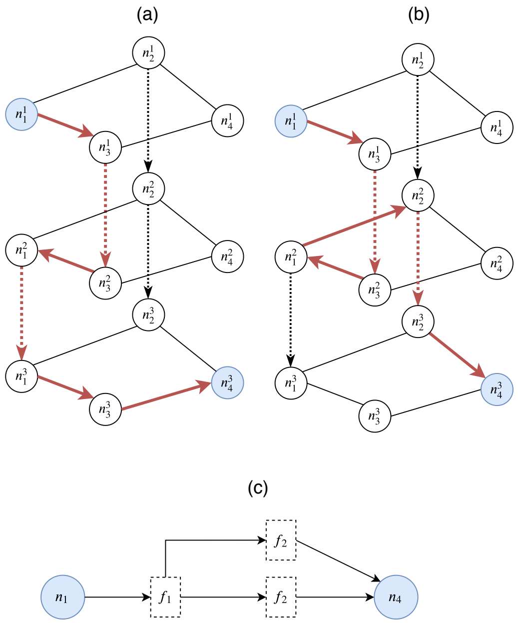
Traffic dynamics

The scale of demands in core networks are large relative to the its routing granularity

- Leverage service composition to provide a splittable configuration in dynamic manner (i.e., with NF splitting and/or multipath routing)

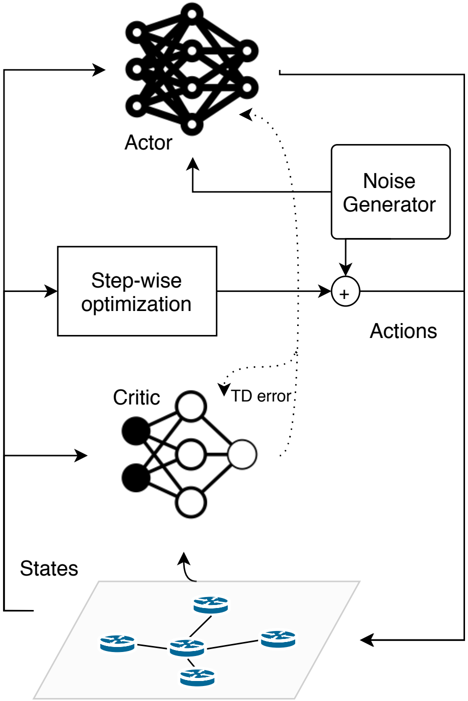
Service Composition and Pre-processing Stage

- Service composition:
  - maintain balance among multiple resources
  - Cater toward time-varying traffic patterns
  - Need to discourage changing topology due to overhead
- Pre-processing stage:
  - Think of service topology in terms of paths
  - Find several paths $\mathcal{P} = \{P_1, P_2, \ldots, P_{|\mathcal{P}|}\}$ that connects $s - t$ through required NFs
  - Reduces state space
  - Provides E2E abstraction to RL action space



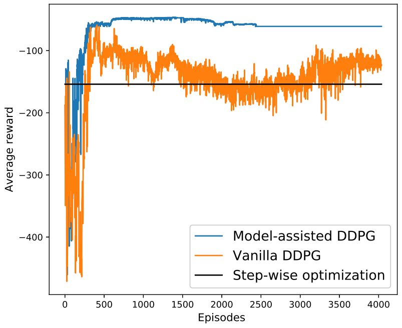
Model-assisted Deep Reinforcement Learning

- Continuous control problem
  - Use actor-critic architecture with deep deterministic policy gradient (DDPG) learning algorithm
- The problem contains:
  - strongly conflicting objectives
  - sparse events
- Use model-assisted exploration:
  - With small decaying probability, invoke MILP solution for optimal step-wise decision



Performance Analysis

- We compare with two benchmarks:
  - Step-wise optimization
  - Vanilla DDPG
- Employ 2 hidden feed-forward neural networks
- Learning rates for actor and critic is 10^{-4} and 10^{-3}
- Probability of invoking model-based solution to $\epsilon = 0.08$
- Both learning approaches outperform step-wise optimization
- Vanilla DDPG is slow to converge (if it does), and is not consistent



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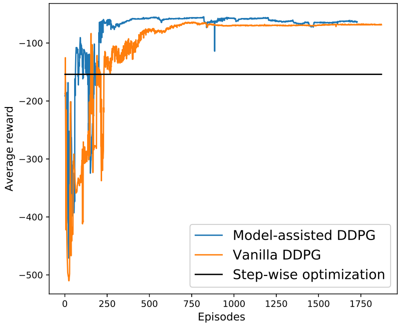


(a)

Outline

Conclusions

This thesis investigates the orchestration and provisioning for NFV-enabled network services with emphasis on practical and flexible design considerations

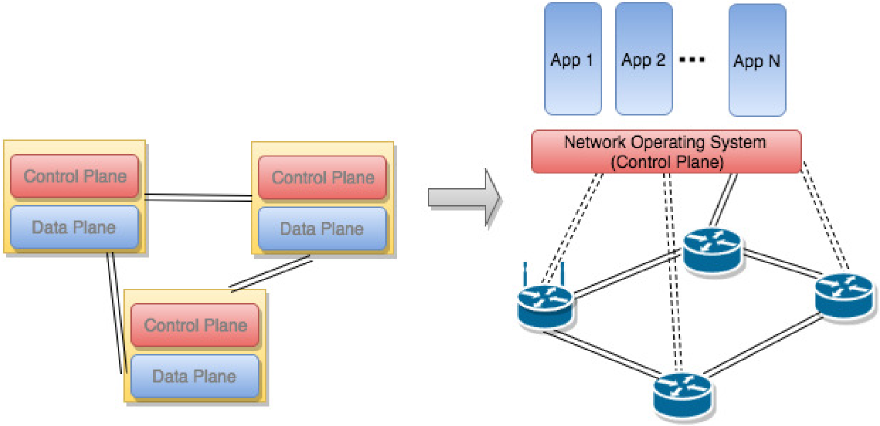
- Joint multicast routing and NF placement framework
  - ILP and MILP formulations for single- and multiple-service scenarios
  - Modular heuristic algorithms to orchestrate the requests
  - Framework enables many-to-one and one-to-many NF mappings with multipath routing
- Online joint composition, routing and NF placement framework
  - Primal-dual based online algorithm
  - Provable performance
  - General for both unicast and multicast services while taking into account the heterogeneity of NFs
- Dynamic provisioning framework with time-varying traffic requirements
  - Deep reinforcement learning approach
  - Model-assisted exploration is developed to increase efficiency and consistency of learning

Thank you!

Backup slides

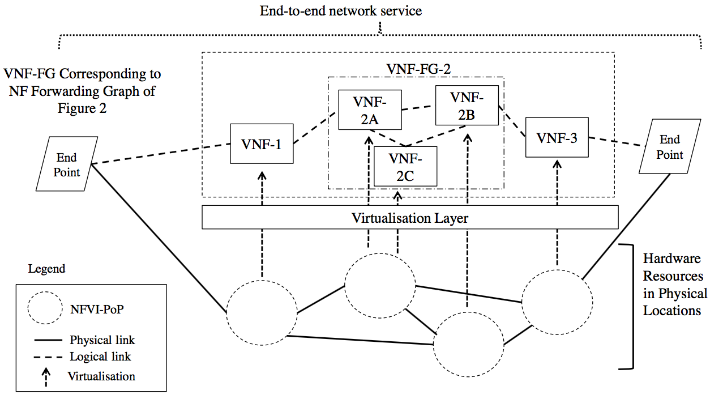
Software Defined Networking

- Coined by Kate Greene; used to describe the OpenFlow platform
- SDN
  - Decoubles the control plane from the data plane
  - Provides programmability to the control plane



Network Function Virtualization

- Proprietary physical devices (middlewares) are virtualized into virtual network functions (NFs)



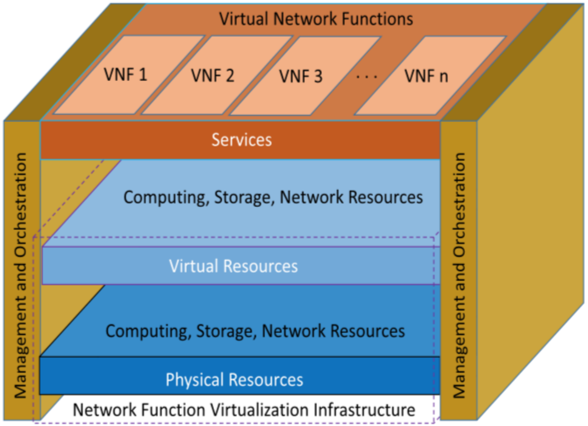


Illustration of multipath routing

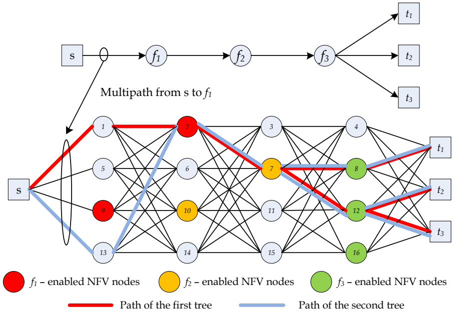
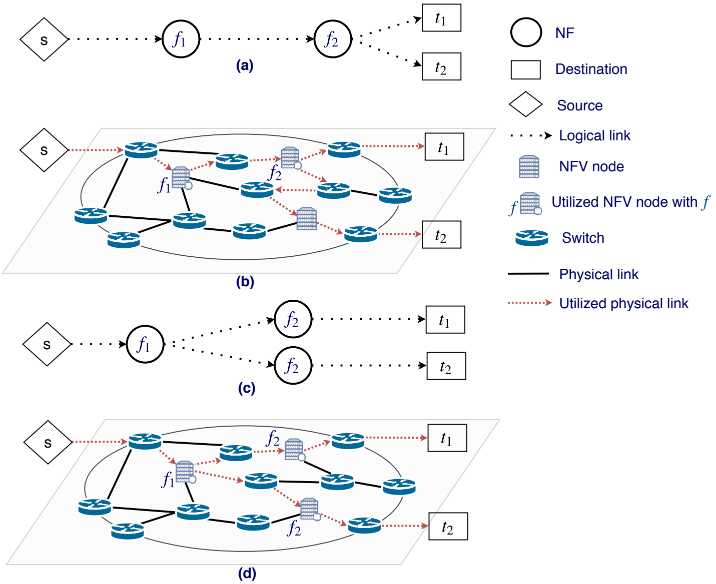


Illustration of 1:n and n : 1 mapping



ILP Formulation (1/2)

Assume that there exists up to J multicast trees to deliver one multicast service from the source to destinations

$$\min \sum_{l \in \mathcal{L}} \sum_{j=1}^{J} \sum_{i=0}^{|\mathcal{V}|} \alpha \left(\frac{r_{li}^{j}}{B(l)} + x_{li}^{j} \right) + \beta \sum_{i=1}^{|\mathcal{V}|} \sum_{n \in \mathcal{M}} \frac{C(f_i)}{C(n)} z_{ni}$$

- Routing (transmission) and placement (processing) cost

- subject to

$$y_{lit}^{j} \leq x_{li}^{j}, \ l \in \mathcal{L}, i \in \mathcal{S}_0^{|\mathcal{V}|}, j \in \mathcal{S}_1^{J}, t \in \mathcal{D}$$

$$u_{nit} \leq z_{ni}, n \in \mathcal{N}, i \in \mathcal{S}_1^{|\mathcal{V}|}, t \in \mathcal{D}.$$

$$x_{li}^{j} \leq \pi^{j}, \ y_{lit}^{j} \leq \pi^{j}, d_r^{j} \leq \pi^{j} \bar{d}_r$$

$$\sum_{j=1}^{J} d_r^{j} = \bar{d}_r$$

- Aggregate constraints, essential for relating x_{lit}, u_{nit} with x_{li}, z_{ni} and π^j

- Data rate split among J trees for one service request

ILP Formulation (2/2)

$$\sum_{(n,m)\in\mathcal{L}} y^j_{(n,m)it} - \sum_{(m,n)\in\mathcal{L}} y^j_{(m,n)it} = \pi^j \left(u_{n(i+1)t} - u_{nit}\right)$$

- Flow routing and placement constraints

$$\sum_{n\in\mathcal{M}} u_{nit} = 1,\ t \in \mathcal{D},\ i \in \mathcal{S}_1^{|V|}$$

- For each $s - t$ pair, one instance of f_i is implemented

$$\sum_{j=1}^{J} \sum_{i=0}^{|\mathcal{V}|} r^j_{li} \le B(l), l \in \mathcal{L}.$$

- Transmission resource constraint

$$\sum_{i=1}^{|\mathcal{V}|} z_{ni} C(f_i) \le C(n), \forall n \in \mathcal{M}$$

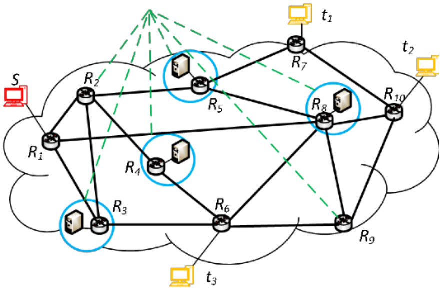
- Processing resource constraint

$$z_{ni} U(n,i) = 1,\ \forall n \in \mathcal{M}, i \in \mathcal{S}_1^{|\mathcal{V}|}$$

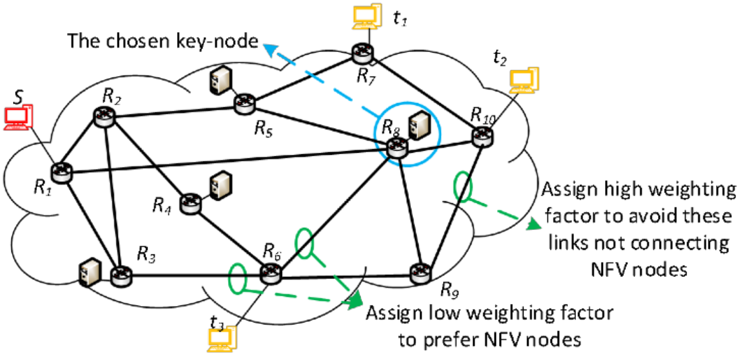
- Restriction on type of functions, admittable for each NFV node

Heuristic Algorithm (single-path)

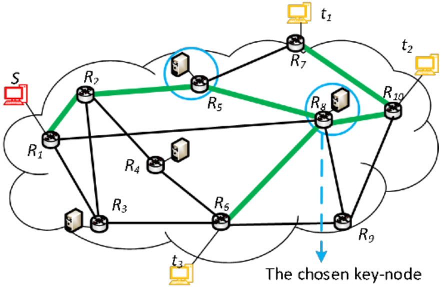
Step 1: Pick an initial key-preferred NFV node



Step 2: Re-weigh links to favor paths with NFV nodes



Step 3: Construct MST for $\{s, \mathcal{D}, \text{keynode}\}$

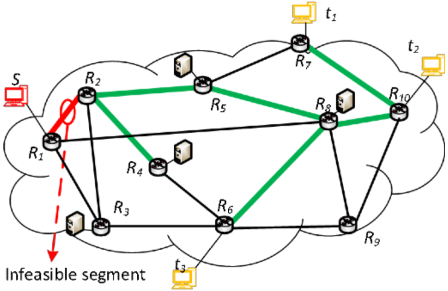


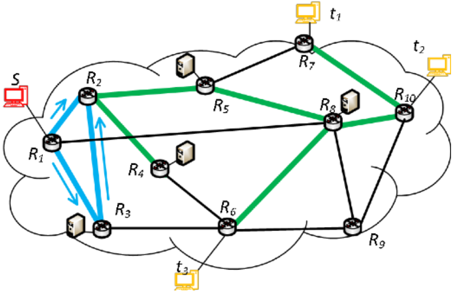
- Step4: Greedily place NFs from $s \rightarrow t$
- Step 5: Repeat steps 1 to 4 by varying key NFV node to maximize number of initialized NFs and minimize the overall provisioning cost.

Heuristic Algorithm (multipath)

- Extension to multipath routing

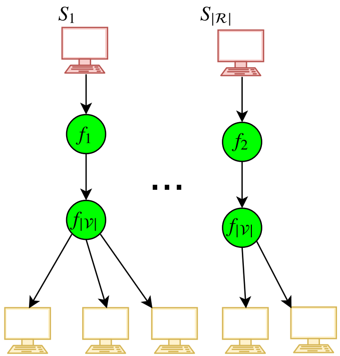
1. Rank all candidate paths for each $(f_i - f_{i+1})$ virtual segument in a descending order based on the amount of residual transmission resources
2. Sequentially choose the paths from, such that the summation of all chosen paths' residual transmission meets the required data rate

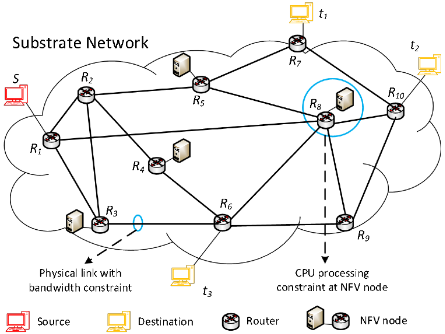




Joint Routing and NF Placement for multi-service scenario

- Input:
  - Physical substrate $\mathcal{G} = (\mathcal{V}, \mathcal{L})$
  - Multicast VNF chains $S_r = (s, \mathcal{D}, f_1, f_2, \ldots, f_{|\mathcal{V}|}, \overline{d}_r)$, $r \in \mathcal{R}$
- Output:
  - Embedded multicast topology for accepted VNF chains on the physical substrate
- Description:
  - To find an optimal combination of multicast NF chains that maximize the overall throughput of the network substrate, while minimizing the respective function and link provisioning costs





MILP Problem Formulation

- Cast as two-step MILP

(P2 − 1)

$$\max_{\boldsymbol{x},\boldsymbol{y},\boldsymbol{z},\boldsymbol{u},\boldsymbol{\rho},\boldsymbol{\pi},\boldsymbol{w},\boldsymbol{d},\boldsymbol{r}} \sum_{r\in\mathcal{R}} R^r \rho^r$$

- (P2-1) To find the maximum throughput R^*

(P2 − 2)

$$\min \sum_{r\in\mathcal{R}} \sum_{l\in\mathcal{L}} \sum_{j\in\mathcal{S}_1^J} \sum_{i=0}^{|\mathcal{V}^r|} \alpha\left(\frac{r_{lij}^r}{B(l)} + x_{lij}^r\right) + \sum_{r\in\mathcal{R}} \sum_{i=1}^{|\mathcal{V}^r|} \sum_{n\in\mathcal{N}} \beta \frac{C(f_i^r)}{C(n)} z_{ni}^r$$

$$\text{s.t.} \quad \sum_{r\in\mathcal{R}} R^r \rho^r \geq \mathbb{R}^*$$

- (P2-2) To minimize the function and link provisioning costs for all admitted services subject to the maximum achievable throughput R^*

Heuristic Solution

- Key strategy
  - To selectively prioritize the network services contributing significantly to the overall throughput with least provisioning cost
  - The first metric is the throughput

$$R^r = a_1 \sum_{i=1}^{|\mathcal{V}^r|} C(f_i^r) + a_2\Big(|\mathcal{V}^r| + |\mathcal{D}^r|\Big)\overline{d^r}, \quad r \in \mathcal{R}.$$

  - The second metric is the distributive level

$$g^r = \frac{A^r q^r}{Aq}, \quad r \in \mathcal{R}.$$

where A^r/A is the smallest normalized convex polygon that spans all destinations, and q^r/q is the normalized distance from source to the center point of the set of destinations for each service

  - Prioritize based on the size (descending order)

$$U^r = R^r(1 - g^r), \quad r \in \mathcal{R}$$

Primal-dual Schema | Dual

- Path-based formulation: need not be solved explicitely

- Formulation:
  - All the possible paths/trees given by set $\mathcal{P}(r)$
  - Let P ($\in \mathcal{P}(r)$) be a path/tree on the network substrate
  - Flow variable: y_P^r as the fraction of flow allocated for service S^r along path P ($\in \mathcal{P}(r)$)
- Objective functions:
  - Choose subset of NFV-enabled services to accept, and their fractional allocation such that profit is maximized
- Constraints:
  - Data rate constraint
  - Transmission resource constraint
  - Processing resource constraint

$$\max \alpha \sum_{S^r \in \sigma} \sum_{P \in \mathcal{P}(r)} \varrho^r y_P^r + \beta \sum_{S^r \in \sigma} \sum_{P \in \mathcal{P}(r)} \rho^r y_P^r \tag{3a}$$

subject to :

$$\forall S^r \in \sigma : \sum_{P \in \mathcal{P}(r)} y_P^r \leq 1 \tag{3b}$$

$$\forall l \in \mathcal{L} : \sum_{S^r \in \sigma} \sum_{P \in \mathcal{P}(r) | l \in P} d^r y_P^r \leq B(l) \tag{3c}$$

$$\forall n \in \mathcal{N} : \sum_{S^r \in \sigma} \sum_{P \in \mathcal{P}(r) | n \in P} C(f^r) y_P^r \leq C(n) \tag{3d}$$

$$\forall S^r \in \sigma, P \in \mathcal{P}(r) : \ y_P^r \geq 0. \tag{3e}$$

Primal-dual Schema | Primal

- Derive primal formulation (Tableau method)
- Primal variables:
  - $\bar{x}(l)$ is the cost of physical link l ($\in \mathcal{L}$)
  - $\tilde{x}(n)$ is the cost of NFV node n ($\in \mathcal{N}$)
  - z^r is zero when service r is rejected
- Interpretation:
  - Minimize the provisioning cost with respect to cost functions, $\bar{x}(l)$, $\tilde{x}(n)$, and z^r

Primal

$$\min \sum_{l \in \mathcal{L}} B(l)\,\bar{x}(l) + \sum_{n \in \mathcal{N}} C(n)\,\tilde{x}(n) + \sum_{S^r \in \sigma} z^r \tag{4a}$$

subject to :

$$\forall S^r \in \sigma, P \in \mathcal{P}(r) : \sum_{l \in P \cap \mathcal{L}} d^r \bar{x}(l) + z^r \geq \alpha \varrho^r \tag{4b}$$

$$\forall S^r \in \sigma, P \in \mathcal{P}(r) : \sum_{n \in P \cap \mathcal{N}} \tilde{x}(n) + z^r \geq \beta \rho^r \tag{4c}$$

$$\forall S^r \in \sigma, l \in \mathcal{L}, n \in \mathcal{N} : z^r, \bar{x}(l), \tilde{x}(n) \geq 0. \tag{4d}$$

Primal-dual Schema | The Approach (1/2)

Competitive Ratio

For a profit-maximization problem, let $A_{\mathrm{OPT}}(\sigma)$ be the profit of the (optimal) offline solution for a sequence of requests (σ). An online algorithm is c-competitive if the produced solution is feasible and its profit is at least $^{A_{\mathrm{OPT}}(\sigma)}/_{c} - e$, where e is an additive term that is independent of the service requests [1].

Let J and A be the value of the objective function of the primal and the dual

$$A \leq J \text{ (using weak duality)}$$

Need to bound dual and primal such that

$$J \leq 2\xi A \tag{5}$$

where 2ξ is the competitive ratio.

[1] N. Buchbinder and J. S. Naor, "The design of competitive online algorithms via a primal-dual approach," Foundations and Trends in Theoretical Comput. Sci., vol. 3, no. 2–3, pp. 93–263, 2009.

Primal-dual Schema | The Approach (2/2)

However, services arrive in an online manner. Therefore, bound the change in each step [1]:

$$\frac{\partial J}{\partial y_P^r} \leq 2\xi \frac{\partial A}{\partial y_P^r}, \quad S^r \in \sigma, \tag{6}$$

while maitaining all constraints satisfied

Solve for:

How do you find link costs $\bar{x}(l)$, node costs $\tilde{x}(n)$, and primal-generated variable z^r such that $\frac{\partial J}{\partial y_P^r} \leq 2\xi \frac{\partial A}{\partial y_P^r}, \quad S^r \in \sigma$, while maintaining all constraints satisfied

In our case:

$$\sum_{l \in \mathcal{L}} B(l) \frac{\partial \bar{x}(l)}{\partial y_P^r} + \sum_{n \in \mathcal{N}} C(n) \frac{\partial \tilde{x}(n)}{\partial y_P^r} + \frac{\partial z^r}{\partial y_P^r} \leq 2\varphi\alpha\varrho^r + 2\phi\beta\rho^r, \, S^r \in \sigma \tag{7}$$

where $\xi = \max\{\varphi, \phi\}$, while maintaining all constraints satisfied

[1] N. Buchbinder and J. S. Naor, "The design of competitive online algorithms via a primal-dual approach," Foundations and Trends in Theoretical Comput. Sci., vol. 3, no. 2–3, pp. 93–263, 2009.

Primal-dual Schema | The Approach (2/2)

Solve for:

How do you find link costs $\bar{x}(l)$, node costs $\tilde{x}(n)$, and primal-generated variable z^r such that $\frac{\partial J}{\partial y_P^r} \leq 2\xi \frac{\partial A}{\partial y_P^r}, \quad S^r \in \sigma$, while maintaining all constraints satisfied

- Take advantage from the seperability of the profit function
- Need to satisfy:

$$\sum_{l \in \mathcal{L}} B(l) \frac{\partial \bar{x}(l)}{\partial y_P^r} \leq 2\varphi\alpha\varrho^r \tag{8}$$

$$\sum_{n \in \mathcal{N}} C(n) \frac{\partial \tilde{x}(n)}{\partial y_P^r} \leq 2\phi\beta\rho^r$$

$$\frac{\partial z^r}{\partial y_P^r} \leq 0$$

where $\xi = \max\{\varphi, \phi\}$, while maintaining all constraints satisfied

Primal-dual Schema | Admission Mechanism

The rth service request is accepted if there exists a path, P, such that:

$$\sum_{l \in P \cap \mathcal{L}} d^r \bar{x}^{r-1}(l) \leq \alpha \varrho^r \tag{9}$$

$$\sum_{n \in P \cap \mathcal{N}} C(f^r) \tilde{x}^{r-1}(n) \leq \beta \rho^r \tag{10}$$

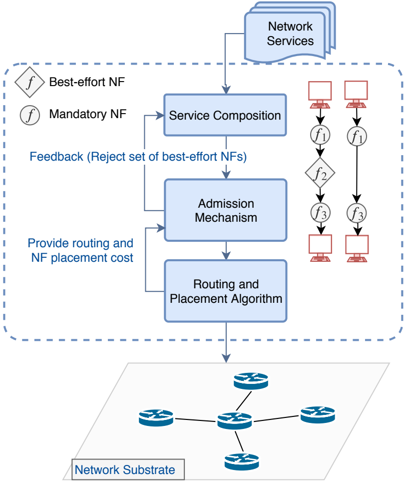
If the two conditions are satisfied, accept the request and route it on P, and set $y^r_P = 1$. Then, update

$$z^r = \max \left(\alpha \varrho^r - \sum_{l \in P \cap \mathcal{L}} d^r \bar{x}(l), \beta \rho^r - \sum_{l \in P \cap \mathcal{N}} C(f^r) \tilde{x}(n) \right) \tag{11}$$

$$\bar{x}^r(l) = \bar{x}^{r-1}(l) e^{\varphi \frac{d^r}{B(l)}} + \frac{1}{L}(e^{\varphi \frac{d^r}{B(l)}} - 1), \quad l \in P \cap \mathcal{L}$$

$$\tilde{x}^r(n) = \tilde{x}^{r-1}(n) e^{\phi \frac{C(f^r)}{C(n)}} + \frac{1}{K}(e^{\phi \frac{C(f^r)}{C(n)}} - 1), \quad n \in P \cap \mathcal{N}$$

where L and K are maximum number of hops and number of NFs



Primal-dual Schema | Admission Mechanism | Best-effort Treatment

The rth service request is accepted if there exists a path, P, such that:

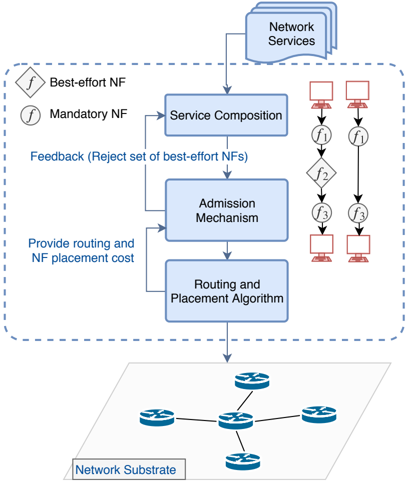
$$\sum_{l \in P \cap \mathcal{L}} d^r \bar{x}^{r-1}(l) \leq \alpha \varrho^r \tag{12}$$

$$\sum_{n \in P \cap \mathcal{N}} C(f^r) \tilde{x}^{r-1}(n) \leq \beta \rho^r \tag{13}$$

Note, eqs. (12), (13) are sufficient yet not necessary conditions.

Treatment of best-effort NFs:

- First, find routing and NF placement configuration that includes best-effort NFs with profit $\rho^r = C(f^r)\eta_b^r$. If rejected, find another configuration that excludes the set of best-effort NF with profit $\rho^r = C(f^r)\eta_m^r$



Primal-dual Schema | Admission Mechanism | Provable Performance

Theorem 1

The competitive ratio of the admission mechanism is $\mathcal{O}(\max(\varphi, \phi))$, where $d^r \leq \frac{\min_{l \in \mathcal{L}} B(l)}{\varphi}$, $C(f^r) \leq \frac{\min_{n \in \mathcal{N}} C(n)}{\phi}$, $\varphi \geq \ln(\alpha L |\mathcal{D}|^k_{\max} + 2)$, and $\phi \geq \ln(\beta K \frac{\eta_{\max}}{\eta_{\min}} + 2)$

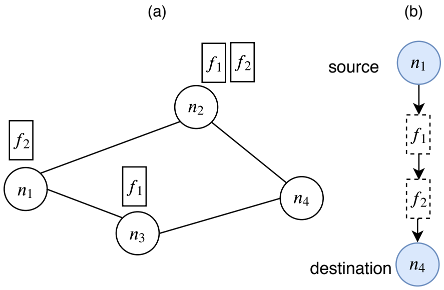
- Only assumption
  - Data rate and processing requirements should be 'small enough' to be accepted
- Competitive ratio
  - is logarithmic in L, K, $|\mathcal{D}|^k_{max}$, and $\frac{\eta_{\max}}{\eta_{\min}}$
  - There exists tradeoff between fairness and optimality concerning type of service (unicast vs. multicast)
  - There exists tradeoff between variability of incentive and optimality concerning heterogeniety of NFs

But, how to find an approximation algorithm for the cheapest routing and NF placement configuration for the constrained scenario

Primal-dual Schema | Routing and NF Placement solution

- The joint routing and NF placement problem for constrained scenario is NP-hard
- Solution:
  - We show that, if a service is accepted with $\varphi \geq \ln(2\alpha L|\mathcal{D}|^{k}_{\max} + 2)$, and $\phi \geq \ln(2\beta K \frac{\eta_{\max}}{\eta_{\min}} + 2)$, the transmission and processing resources cannot not exceeded
  - Therefore, can find exact routing and NF placement algorithm for the unconstrained scenario
- Create multilayer network transformation to transform the unconstrained problem to an equivalent routing problem

Routing and NF Placement | Auxiliary network transformation



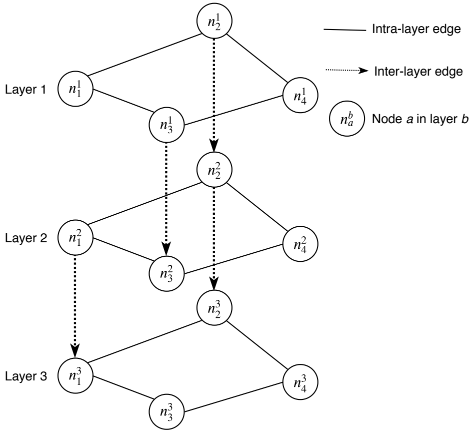
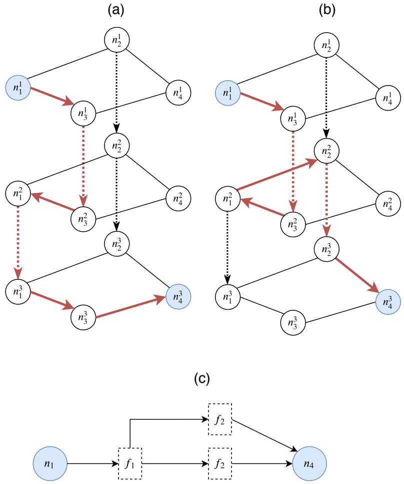


Figure: (Left): (a) A network substrate along with the permissible NFs on each network element, and (b) the logical topology of a service request. (Right) The auxiliary network transformation for the problem input.

Pre-processing for DRL

- Joint dynamic composition, routing, and NF placement framework requires end-to-end solution

- Pre-processing stage:
  - Think of service topology in terms of paths
  - Find several paths $\mathcal{P} = \{P_1, P_2, \ldots, P_{|\mathcal{P}|}\}$ that connects $s - t$ through required NFs



- Pre-processing and state space intuition:
  - $|\mathcal{P}|$ is theoretically large, practically it is not (*in scale-free networks*)
  - Service likely does not meander from shortest-path by a lot
  - Helps reduce state space, as other irrelevant links and nodes can be ignored
  - Abstraction that provides an input to RL framework in action space

Reward Function

- Reward function:
  - Routing: $R_1(\tau) = -\sum_{i=1}^{|\mathcal{V}|}\sum_{l\in\mathcal{L}} a_1\mathbb{I}(\sum_{k=1}^{\Omega} x_{li}^{k}(\tau))$
  - NF setup:
    $R_2(\tau) = -\sum_{n\in\mathcal{N}}\sum_{i=1}^{|\mathcal{V}|} a_2\mathbb{I}\Big(\sum_{k=1}^{\Omega} z_{ni}^{k}(\tau) - \sum_{k=1}^{\Omega} z_{ni}^{k}(\tau-1)\Big)$
  - Transmission: $R_3(\tau) = -\sum_{i\in\mathcal{S}_0^{|\mathcal{V}|}}\sum_{l\in\mathcal{L}}\sum_{k=1}^{\Omega} d\,\frac{f_{li}^{k}(\tau)}{B(l)}$
  - Processing: $R_4(\tau) = -\sum_{i\in\mathcal{S}_1^{|\mathcal{V}|}}\sum_{n\in\mathcal{M}}\sum_{k=1}^{\Omega}\frac{C(f_i^k)}{C(n)} z_{ni}^{k}(\tau)$
- Reward $= \alpha R_1 + \beta R_2 + \gamma R_3 + \zeta R_4$

States and Actions

- Action space:
  - Assigned data rates of each path, e.g.,
  - $\mathcal{A}(\tau) = [d_{P_1}(\tau), d_{P_2}(\tau), d_{P_3}(\tau)]$
- State space:
  - Current data rate, and predicted data rate
  - Record current utilization, and residual bandwidth of network elements of all concerned paths
  - $\mathcal{S}(\tau) = [d(\tau-1), \hat{d}(\tau), U_x(\tau), C_x(\tau)], \forall x \in (\mathcal{N}, \mathcal{L}), \forall P \in \mathcal{P}$
- State space intuition:
  - $|\mathcal{P}|$ is theoretically large, practically it is not (*in scale-free networks*)
  - Service likely does not meander from shortest-path by a lot
  - Need to include background traffic information