Joint VNF Placement and Multicast Traffic Routing in 5G Core Networks

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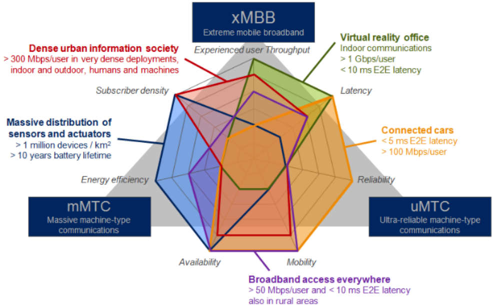
Table of Contents

- Introduction
  - Motivation into 5G Networks
  - Service Customized Virtual Networks
- System Model
- Research Problem
  - Problem Description and Challenges
  - Problem Formulation
  - Heuristic Algorithm
  - Performance Evaluation

5G Networks

- Explosive Increase in demand for capacity and data rates.
- Voice-centric networks to data-centric networks.
- New extreme and agile applications/scenarios.

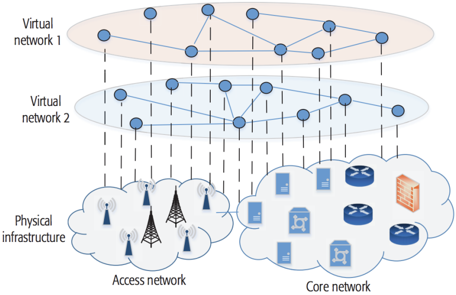


5GPPP classification of 5G use cases [1]

[1] I. D. Silva, S. E. Ayoubi, O. Boldi, Ö. Bulakci, and P. Spapis, "5G RAN Architecture and Functional Design," tech. rep., 5th Generation Public Private Partnership, 2016.

Service Customized Virtual Networks

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

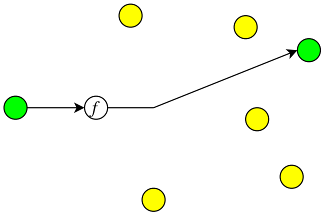


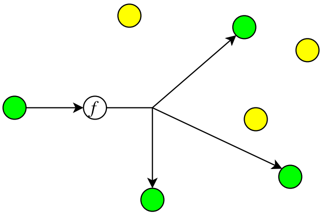
Network virtualization [2]

[2] 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.

Orchestration of NFV-enabled Multicast Services

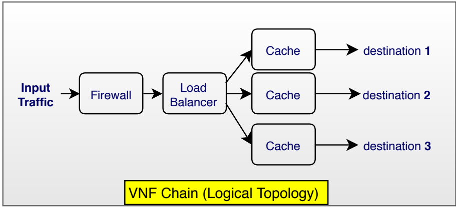
- We focus on the orchestration of multicast NFV-enabled network services.
- Multicast reduces the transmission resource consumption in backbone networks by over 50% compared to unicast.
- Multicast applications are trending, e.g., video streaming, multi-player augmented/virtual applications, and file distribution.





Network Service | Definition

- Network service:
  - Traditional connectivity between terminals.
  - Network application (network policy).
- Example:
  - Distribute firewall-protected web-based traffic to destinations.



Plan

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- Motivation into 5G Networks
- Service Customized Virtual Networks

System Model

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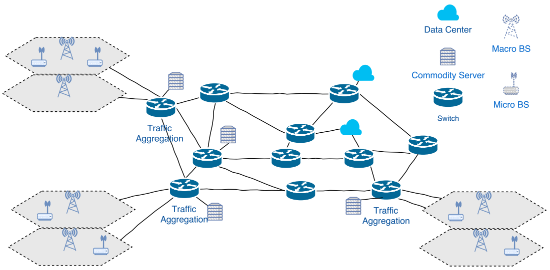
Network Substrate

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

- The nodes can be switches and NFV nodes (set $\mathcal{M}$).
- Each NFV node has available CPU resources, $C(n)$.
- Each physical link has available transmission resource, $B(l)$.
- Each physical node is capable of hosting specific subset of VNFs with indicator function $U(n, i) = 1$, if NFV node n can admit f_i.



Multicast VNF Chain

- A multicast VNF chain is represented by acyclic directed graph,

$$S_r = (\underbrace{s}_{\text{source}}, \underbrace{\mathcal{D}}_{\text{destinations}}, \underbrace{f_1, f_2, \ldots, f_{|\mathcal{V}|}}_{\text{set of ordered functions}}, \underbrace{\overline{d}_r}_{\text{data rate}})$$

- s and $\mathcal{D}$ represent the source node and the set of destinations.
- $\mathcal{V} = \{f_1, f_2, \ldots f_{|\mathcal{V}|}\}$ represents the set of functions that have to be traversed in an ascending order for every source-destination pair.
- $\overline{d}_r$ is the data rate requirement.
- Each VNF f_i, $i \in \{1, \ldots, |\mathcal{V}|\}$, requires computing resources $C(f_i)$.

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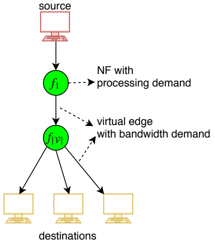
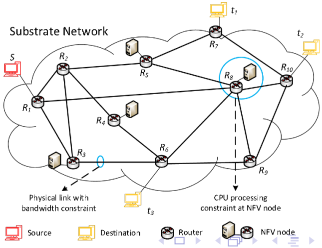
Joint routing and NF placement for multicast services

- Input:
    - Physical substrate $\mathcal{G} = (\mathcal{V}, \mathcal{L})$;
    - Multicast VNF chain $S_r = (s, \mathcal{D}, f_1, f_2, \ldots, f_{|\mathcal{V}|}, \overline{d}_r)$.
- Output:
    - Embedded multicast topology on physical substrate.
- Description:
    - How to jointly embed a multicast service and route traffic between source and destinations through a chain of NFV nodes to minimize the network provisioning cost?





Research Issues

Research Issue 1

Backward-compatible routing frameworks do not apply to this joint problem.

- If no NFs (routing only) $\rightarrow$ reduces to Steiner tree construction.
- In practice, there exist a massive number of NF placement configurations; each of which requires a multicast routing tree construction.

Research Issues

Research Issue 2

Multicast replication points should *not* be limited as a result of placement of NFs.

- Existing works perform NF placement first, followed by multicast routing.
- Results in limiting freedom of replication points.
- Conversely, building a multicast tree, followed by placement of NFs may not always be feasible.

Research Issues

Research Issue 3

(1) The problem input, i.e., physical substrate can relatively be very large;
(2) Developed solution should be relatively quick, in the scale of minutes.

- Depending on the service type and size, network services lives for minutes to several hours.
- There is a need for quick heuristic/approximation algorithms that provide consistent results.

Solving Methodology

Problem Solving Methodology

Develop a *flexible* placement and routing framework with multipath traffic routing. That is, we allow for one-to-many and many-to-one VNF mappings, in addition to multipath routing.

- VNF chain provides traditional connectivity and network application.
  - $1:n$ and $n:1$ mapping $\rightarrow$ flexibility for multicast replication points.
  - Enable Multipath routing.

Solving Methodology

Illustration of multipath routing

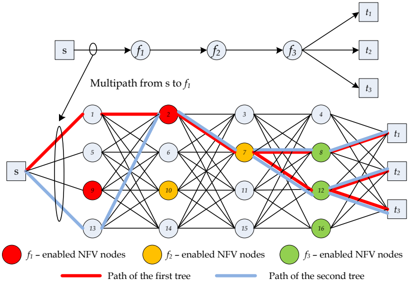
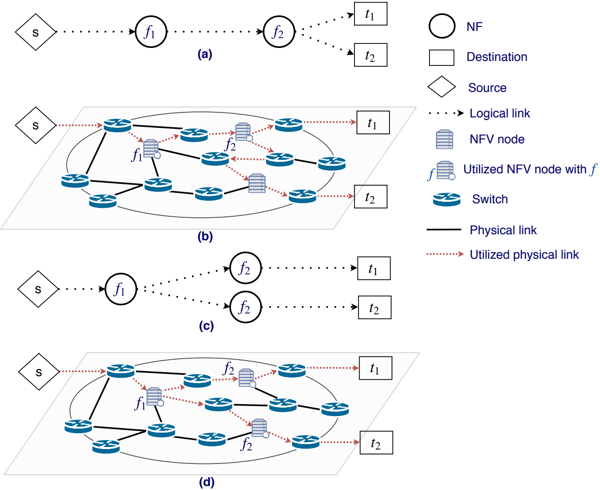


Illustration of 1:n and n : 1 mapping



Problem 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

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

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

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

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

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

- 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

Problem 1 Formulation (2/2)

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

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

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

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

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- Flow routing and placement constraints

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- Flow routing and placement constraints
- For each $s-t$ pair, one instance of f_i is implemented

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- Transmission resource constraint

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

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Problem 1 Formulation (2/2)

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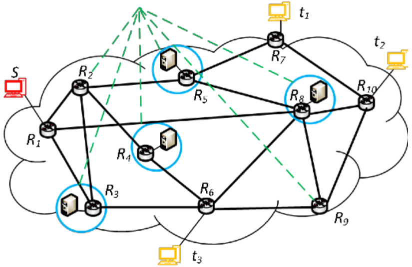
$$z_{ni} U(n,i) = 1,\ \forall n \in \mathcal{M}, i \in \mathcal{S}_1^{|\mathcal{V}|}$$

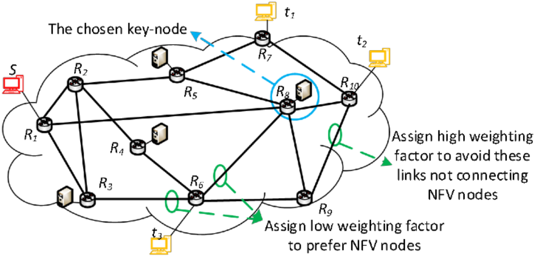
- Restriction on type of functions, admittable for each NFV node

Heuristic Algorithm (single-path)

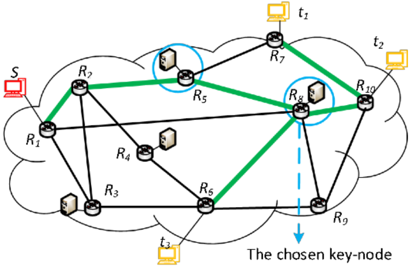
Step 1: Pick an initial key-preferred NFV node



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



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

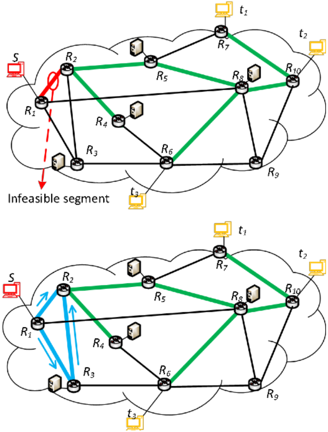


- Step4: Greedily place NFs from $s \rightarrow t$
- Step 5: Repeat steps 1 to 4 by varying key NFV node to maximize number of initialized NFs and minimize the overall provisioning cost.

Heuristic Algorithm (multipath)

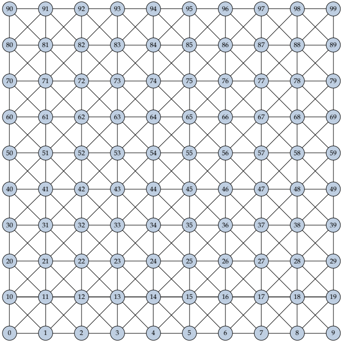
- Extension to multipath routing

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.



Performance Evaluation (1/4)

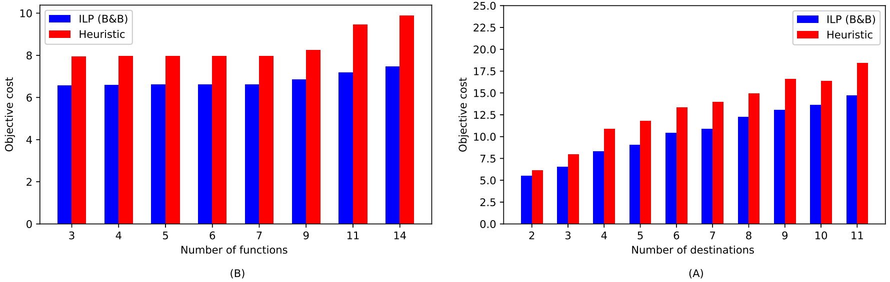
- Simulated physical substrate
  - $|\mathcal{N}| = 100, |\mathcal{L}| = 684$
  - 25% selected NFV nodes
  - processing and transmission $\sim \mathcal{U}(50, 200)$
- Varying multicast requests



Simulated mesh topology [3]

Performance Evaluation (2/4)

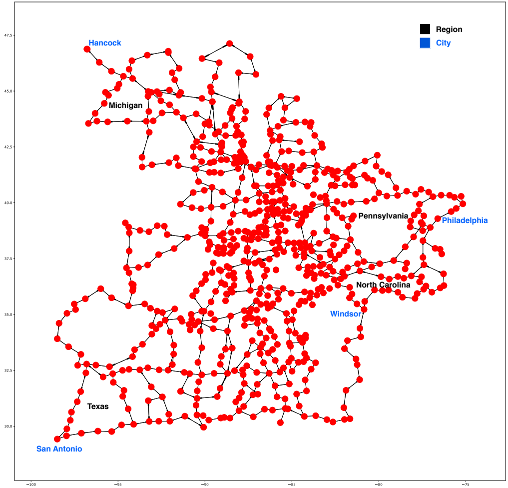
- Numerical results



Comparison between ILP and heuristic algorithm solutions for mesh topology

Performance Evaluation (3/4)

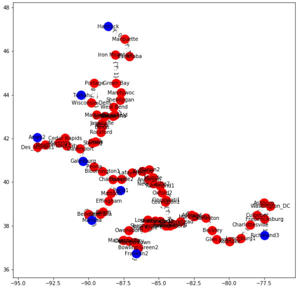
- Large Physical Substrate
  - KDL
  - $|\mathcal{N}| = 726, |\mathcal{L}| = 1636$
  - 25% selected NFV nodes
  - processing and transmission $\sim \mathcal{U}(60, 150), \mathcal{U}(100, 300)$
- Multicast request (SFC)
  - $|\mathcal{V}| = 10, \overline{d} = 10$
  - $\theta = [\frac{1}{2}, 11, ..., 2]$
  - source: Hancock
  - $|\mathcal{D}| = 7$



KDL topology (physical substrate)

Performance Evaluation (4/4)

- Run-time:
  - ILP: 363.43 sec (Python) with $\sim \mathcal{U}(100, 300)$
  - ILP: 67.10 sec (Python) with $\sim \mathcal{U}(60, 150)$
  - Heuristic: $\sim$60 sec (C++) for both
- The run-time of heuristic is more consistent.



References

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Thank You

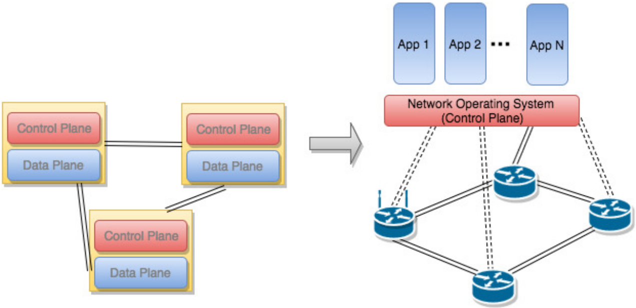
Thank you to the Reviewers

Happy new year!

Backup slides

Software Defined Networking

- Coined by Kate Greene; used to describe the OpenFlow platform.
- SDN is a new conceptual architecture.
  - 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).