SPEED

SFC Placement in Edge-Cloud Continuum: a Distributed Approach

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Agenda

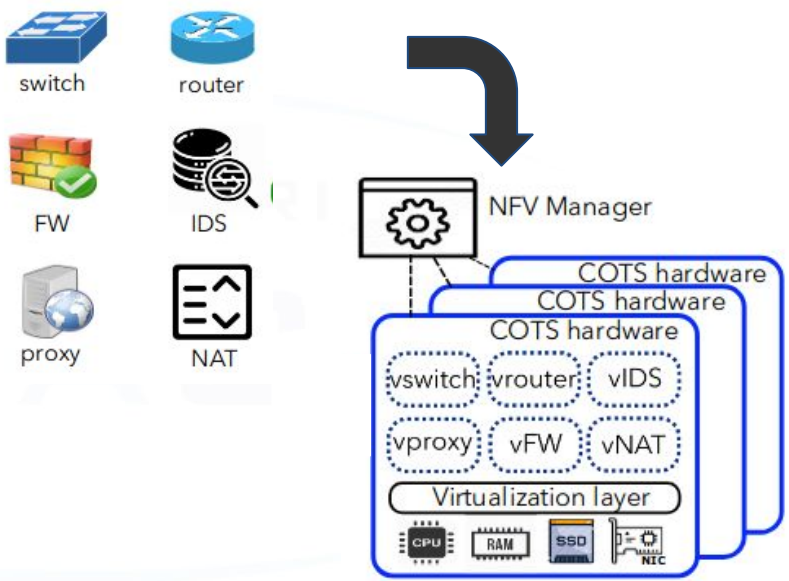
- Introduction
- Problem
- Proposed Solution
- Evaluation
- Conclusion

Introduction

- NFV Paradigm
  - VNF Placement Problem
- Service Function Chain (SFC)
  - SFC Placement Problem
- Distributed Environment
- Game Theory

NFV Paradigm

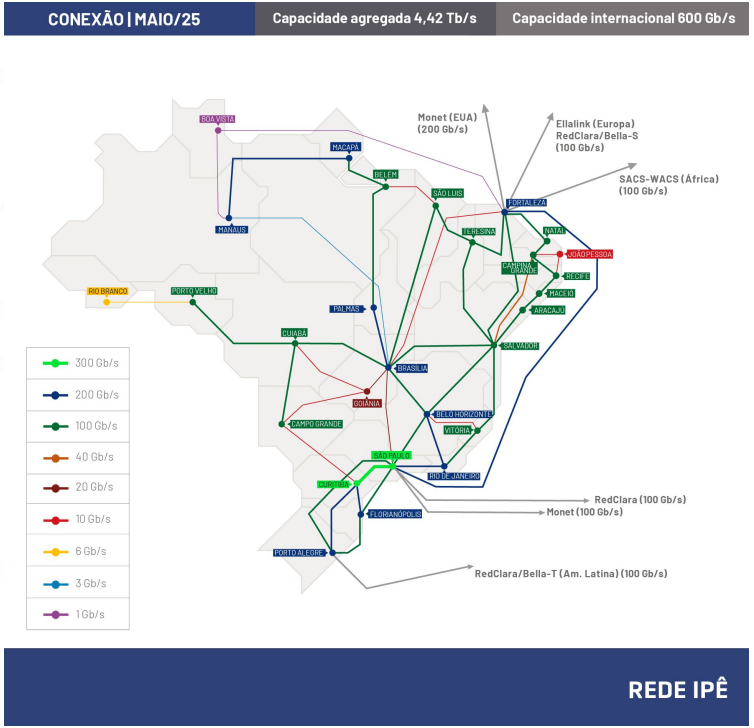
- Is the **virtualization** of the **core network** function as VNFs
  - High-level functions
    - Video encoders
    - Text to speech
- VNF Platforms
  - Management
  - **Orchestration**



T. Zhang, H. Qiu, L. Linguaglossa, W. Cerroni and P. Giaccone, "NFV Platforms: Taxonomy, Design Choices and Future Challenges," in *IEEE Transactions on Network and Service Management*, vol. 18, no. 1, pp. 30-48, March 2021, doi: 10.1109/TNSM.2020.3045381.

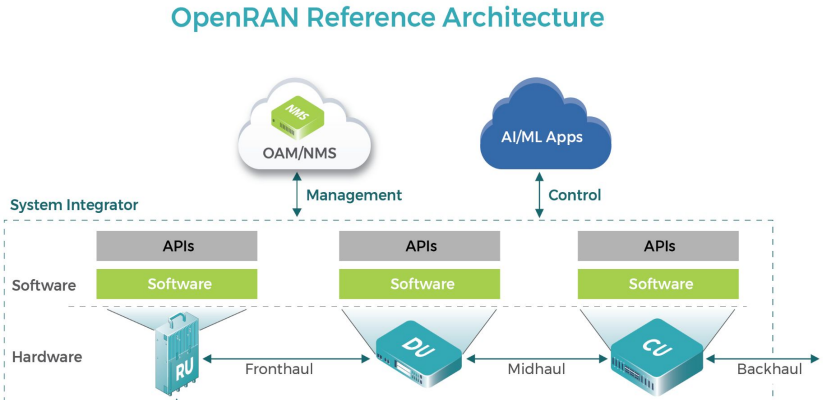
VNF Placement Problem

- VNF Orchestration
  - **VNF Placement Problem**
- Decides which computational node will be used to execute the VNF
  - This problem is **NP-Hard**
    - Requiring good heuristics



SFC Definition

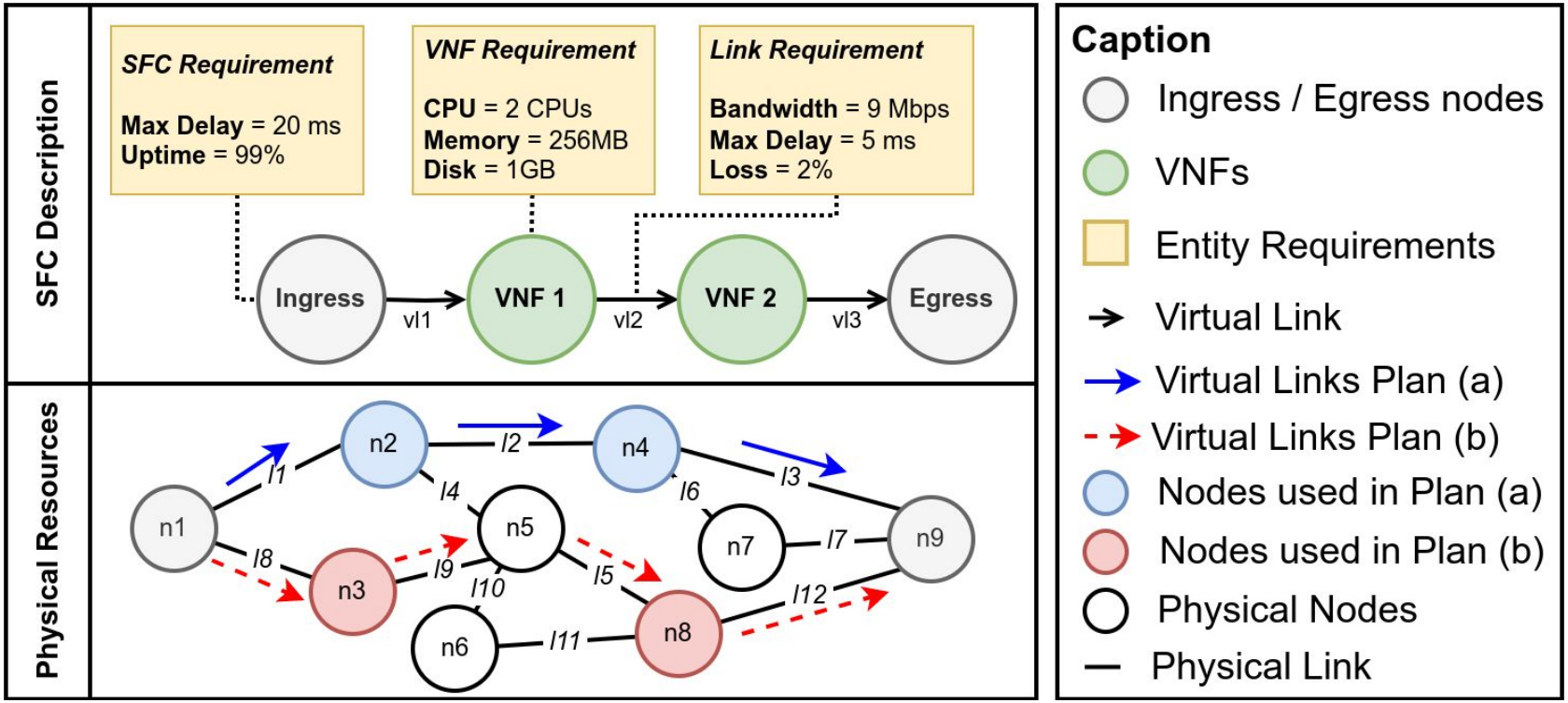
- Virtualizing VNFs **individually is insufficient in some scenarios**
  - Service Function Chain (SFC)
    - SFC enables the dynamic composition and ordered execution of VNFs to deliver end-to-end services



SFC Placement Problem

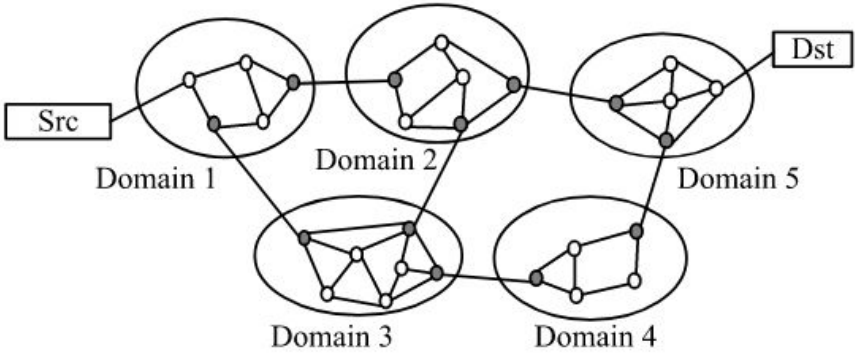
- Now the **SFC Placement Problem** has emerged
- New challenges must be addressed
  - Where to execute each VNF of the requested SFC
  - The networking connectivity creation to enable the flow across all the VNF
- Solved using multiple technologies
  - Integer Linear Programming
  - Tabu search
  - **Game Theory**

SFC Placement Problem



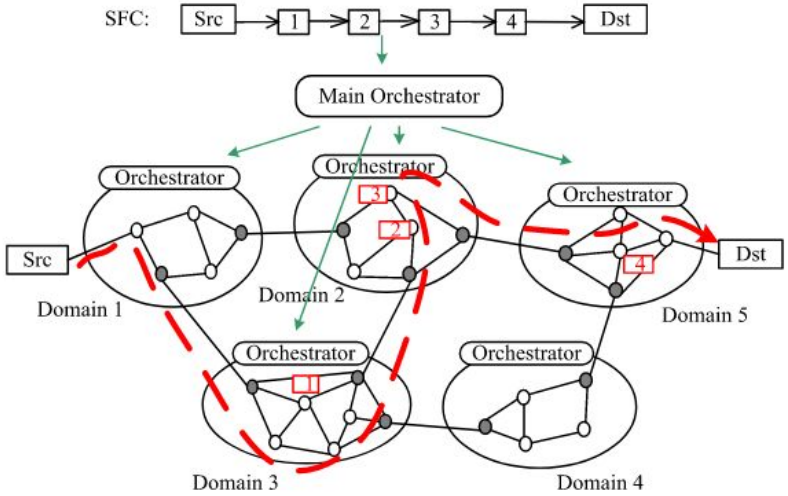
Distributed Environment

- **Edge-Cloud Continuum**
  - Coordination between multiple domains
    - Potentially managed by different service providers



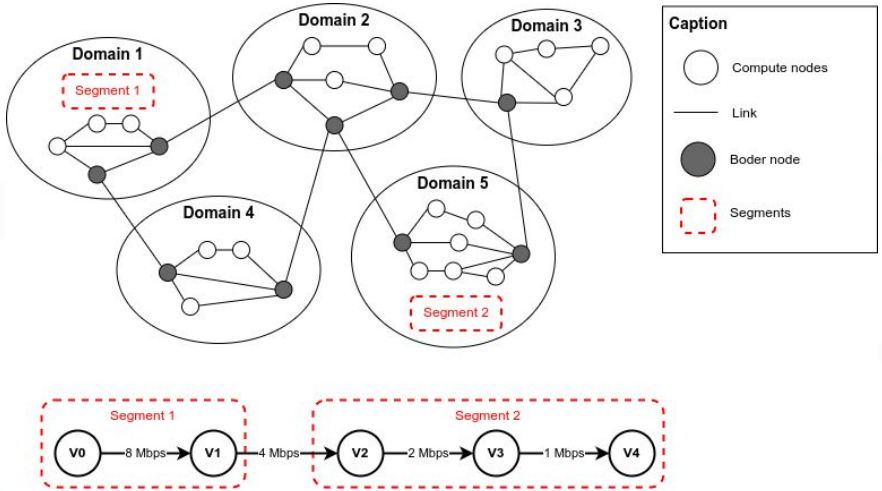
G. Sun, Y. Li, D. Liao and V. Chang, "Service Function Chain Orchestration Across Multiple Domains: A Full Mesh Aggregation Approach," in *IEEE Transactions on Network and Service Management*, vol. 15, no. 3, pp. 1175-1191, Sept. 2018, doi: 10.1109/TNSM.2018.2861717.

Distributed Environment



- **Centralized placement** is unsuitable in large environments
- **Distributed placement** allocates SFC without full knowledge of the environments

Distributed SFC Placement Problem



- Distributed SFC Placement composed of **two phases**:
  a. **Segmentation:** the SFC are divided into segments
  b. **Resource Allocation:** each segment is delivered to a domain

Game Theory

- Game Theory is the study of **strategic interactions** between **decision-makers**
- It analyzes how individuals, groups, or organizations make choices when the **outcome depends on the actions of others**
- Originally developed in economics, Game Theory is now applied in many fields of computer science

Game Theory Key Concepts

- **Players:** the decision-makers involved in the interaction
- **Strategies:** the possible actions each player can take
- **Payoffs:** the outcomes or rewards resulting from the chosen strategies
- **Equilibrium:** a stable situation where no player benefits from changing their strategy alone (e.g., Nash Equilibrium)

Open Problems

1) Even in distributed environment, the **placement plan** is created by only **one domain**
2) The **segments are created** only during the **initialization** of the placement

Goals

- Create a **new method to solve the SFC Placement Problem in a distributed fashion**
  - With segments being created multiple times
    - This combination provides better adaptability in multi-domain environments

Research Questions

Q1: How can Game Theory be used to solve the Service Function Chain Placement Problem (SFCPP) in a multi-domain Edge-Cloud continuum?

Method: This question is addressed through the design and evaluation of a set of algorithms and an architecture that enable the use of Game Theory to solve the SFCPP.

Research Questions

Q2: How does the proposed approach contribute to reducing the monetary cost of executing SFCs in a multi-domain Edge-Cloud continuum?

Method: This question is answered by conducting cost-oriented performance evaluations using scenarios based on realistic infrastructure and traffic parameters.

Research Questions

Q3: How does the proposed approach contribute to increasing the SFC placement success rate in a multi-domain Edge-Cloud continuum?

Method: This question is addressed through experiments measuring placement success rate under varying resource availability and network conditions.

Related Work

Study	Distributed Approach	Segmentation
Chen et al. (2021)	The allocation of each VNF segment in each domain is executed in parallel	Static
Liu et al. (2020)	The auction consensus phase defines which segment will be executed in each domain	Static
Sun et al. (2018)	The allocation of each sub-SFC in each domain is executed in parallel	Static
Avasalcai et al. (2019)	Auction-based with a centralized orchestrator that defines the winner domain for each VNF in the SFC	Static
Gao et al. (2022)	The allocation of each service in each satellite is executed in parallel	No Segments

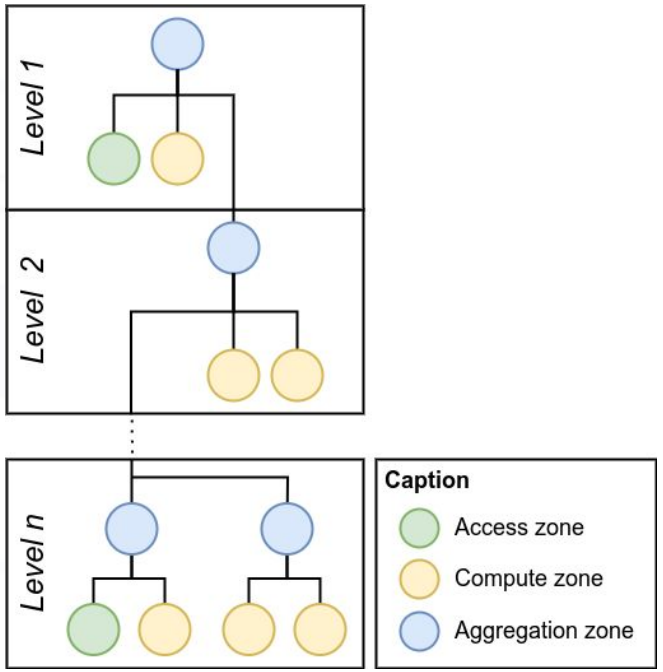
Proposed Solution - SPEED

SFC Placement in Edge-Cloud Continuum: a Distributed Approach

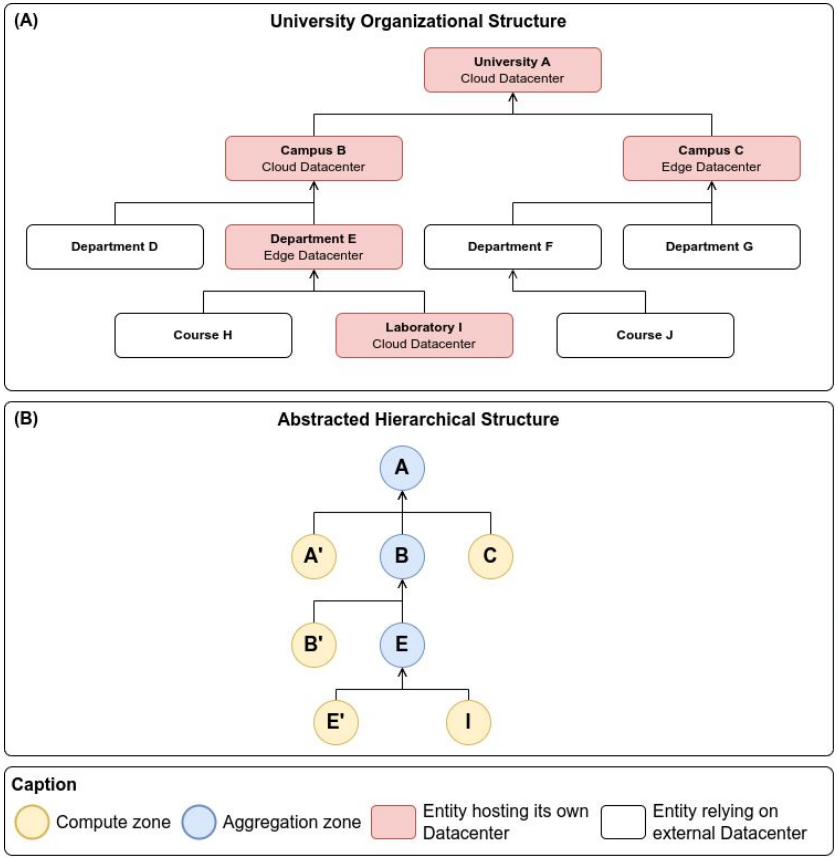
- Hierarchical Organization
- Meta Data Aggregation
- Architectural Components
- The SPEED Approach
  - Manager Zone Selection
  - SFC Segmentation
  - Zone Selection as a Singleton Congestion Game

Hierarchical Organization

- **Access zones** are elements that provide connectivity for the users
- **Compute zones** are the elements that provide computational resources
- **Aggregation zones** are abstracted elements that aggregated the data about the descending zones

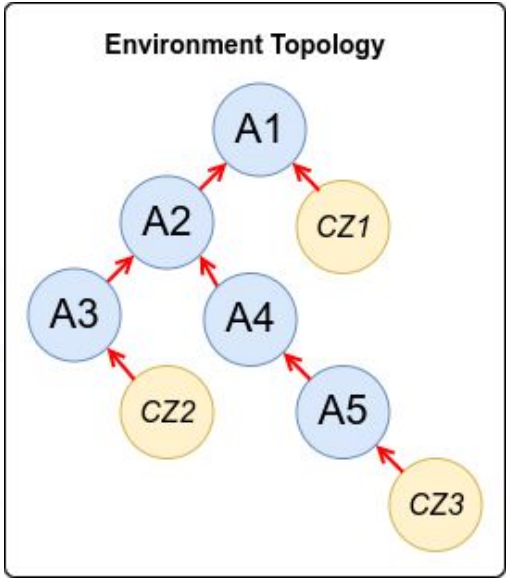


Hierarchical Organization

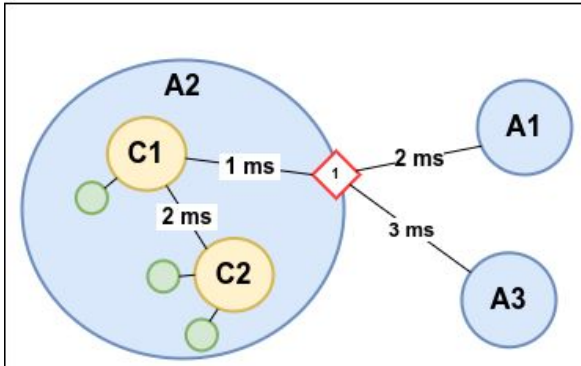


Meta Data Aggregation

- **The Aggregation zones process and store meta data sent by their underlying zones**
  - Zones only send meta data to its parent zone
- The top-level Aggregation zones have aggregated meta data about all the child zones



Meta Data Aggregation Example



Caption

- Gateway
- Access zone
- Compute zone
- Aggregation zone
- VNF Availability Update
- Aggregation Zone Update

[Data Aggregation Over Time]

	T0	T1	T2

Aggregation Zone Data

A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1
C2	4	1	3	1

A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1

A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1
C1	4	1	1	1

Compute Zone Data

C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	4	1	3	1

C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1

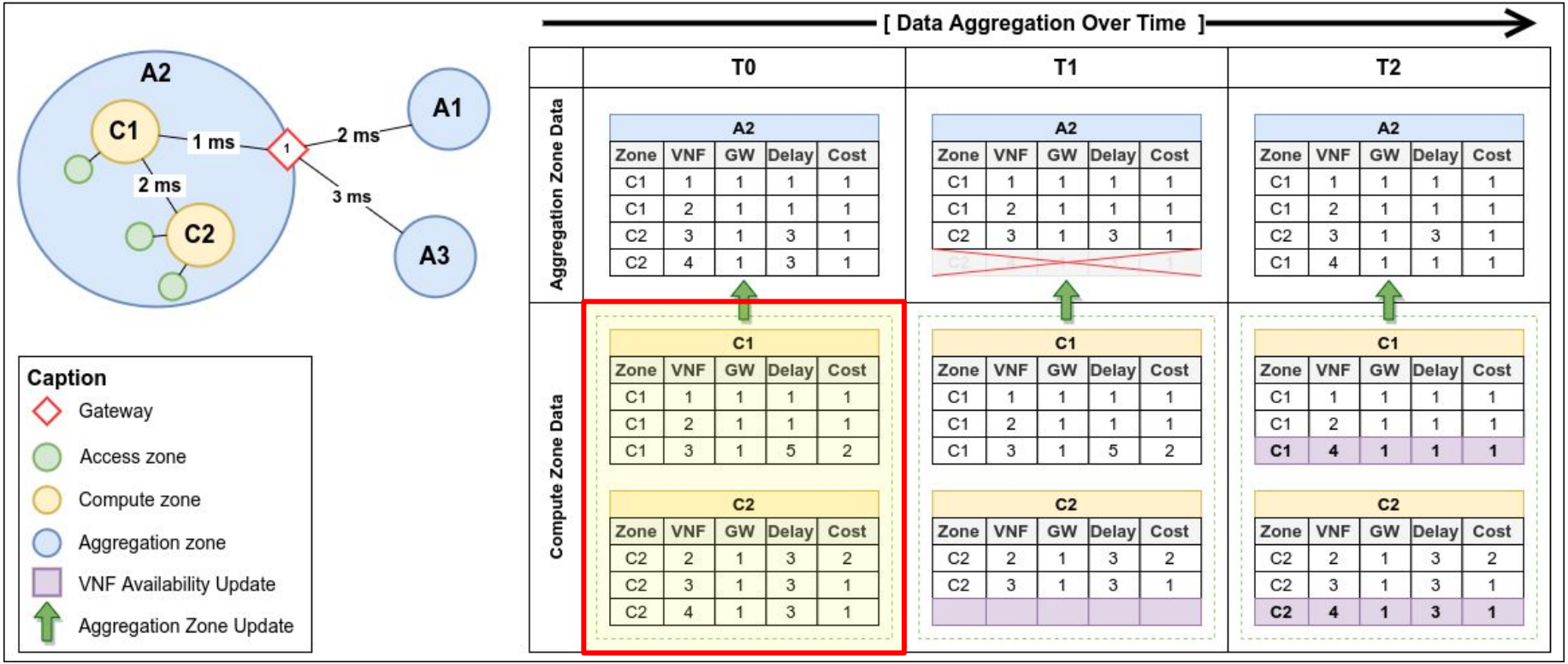
C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	**4**	**1**	**1**	**1**

C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	**4**	**1**	**3**	**1**

Meta Data Aggregation Example



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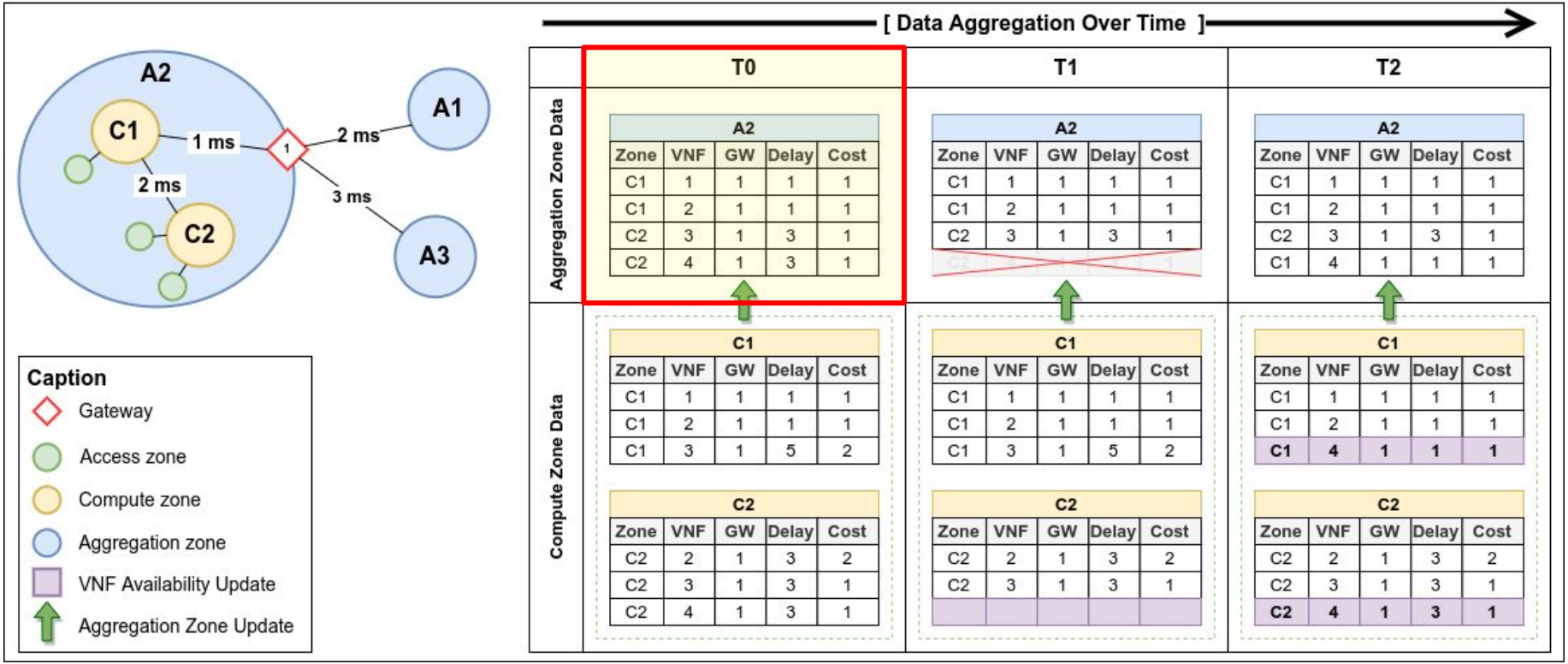

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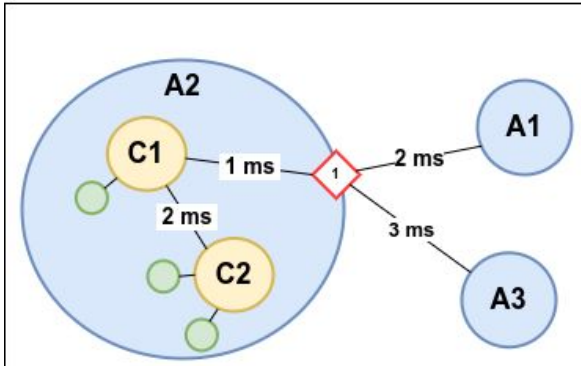

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Aggregation Zone Data

T0

A2

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C2	4	1	3	1

T1

A2

Zone	VNF	GW	Delay	Cost
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C2	3	1	3	1

T2

A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1
C1	4	1	1	1

Compute Zone Data

T0

C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	4	1	3	1

T1

C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1

T2

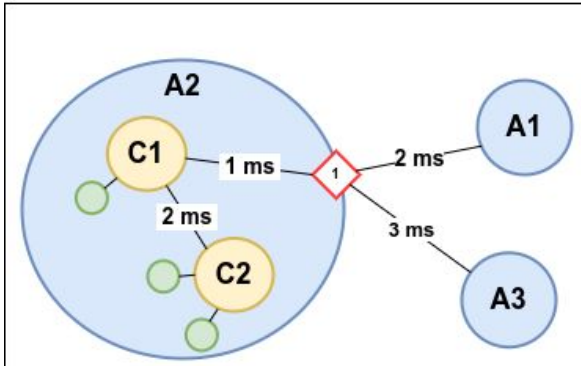
C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	**4**	**1**	**1**	**1**

C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	**4**	**1**	**3**	**1**

Meta Data Aggregation Example



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T1

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T2

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Compute Zone Data

T0

C1

Zone	VNF	GW	Delay	Cost
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C2

Zone	VNF	GW	Delay	Cost
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C2	3	1	3	1
C2	4	1	3	1

T1

C1

Zone	VNF	GW	Delay	Cost
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C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1

T2

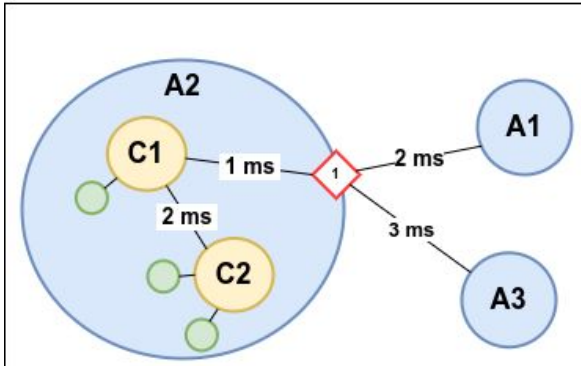
C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	**4**	**1**	**1**	**1**

C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	**4**	**1**	**3**	**1**

Meta Data Aggregation Example



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[Data Aggregation Over Time]

	T0	T1	T2
Aggregation Zone Data	A2	A2	A2
Compute Zone Data	C1 and C2	C1 and C2	C1 and C2

Aggregation Zone Data — A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1
C2	4	1	3	1

Aggregation Zone Data — A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1

Aggregation Zone Data — A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1
C1	4	1	1	1

Compute Zone Data — C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

Compute Zone Data — C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	4	1	3	1

Compute Zone Data — C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

Compute Zone Data — C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1

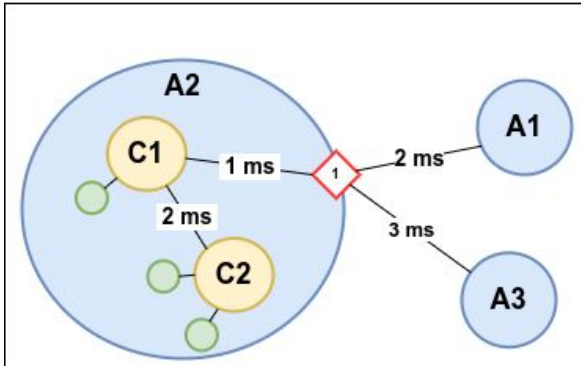
Compute Zone Data — C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	**4**	**1**	**1**	**1**

Compute Zone Data — C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	**4**	**1**	**3**	**1**

Meta Data Aggregation Example



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[Data Aggregation Over Time]

	T0	T1	T2
Aggregation Zone Data	A2	A2	A2
Compute Zone Data	C1 and C2	C1 and C2	C1 and C2

Aggregation Zone Data — A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1
C2	4	1	3	1

T0 — Compute Zone Data — C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

T0 — Compute Zone Data — C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	4	1	3	1

T1 — Aggregation Zone Data — A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1

T1 — Compute Zone Data — C1

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	3	1	5	2

T1 — Compute Zone Data — C2

Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1

T2 — Aggregation Zone Data — A2

Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C2	3	1	3	1
C1	4	1	1	1

T2 — Compute Zone Data — C1

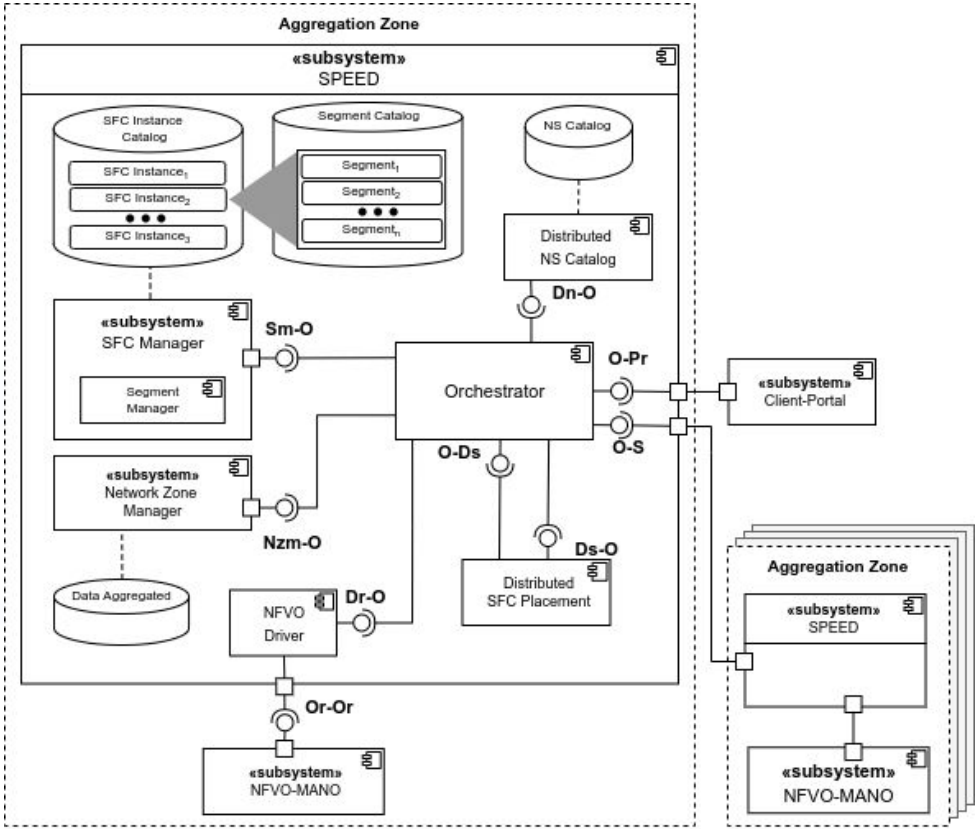
Zone	VNF	GW	Delay	Cost
C1	1	1	1	1
C1	2	1	1	1
C1	**4**	**1**	**1**	**1**

T2 — Compute Zone Data — C2

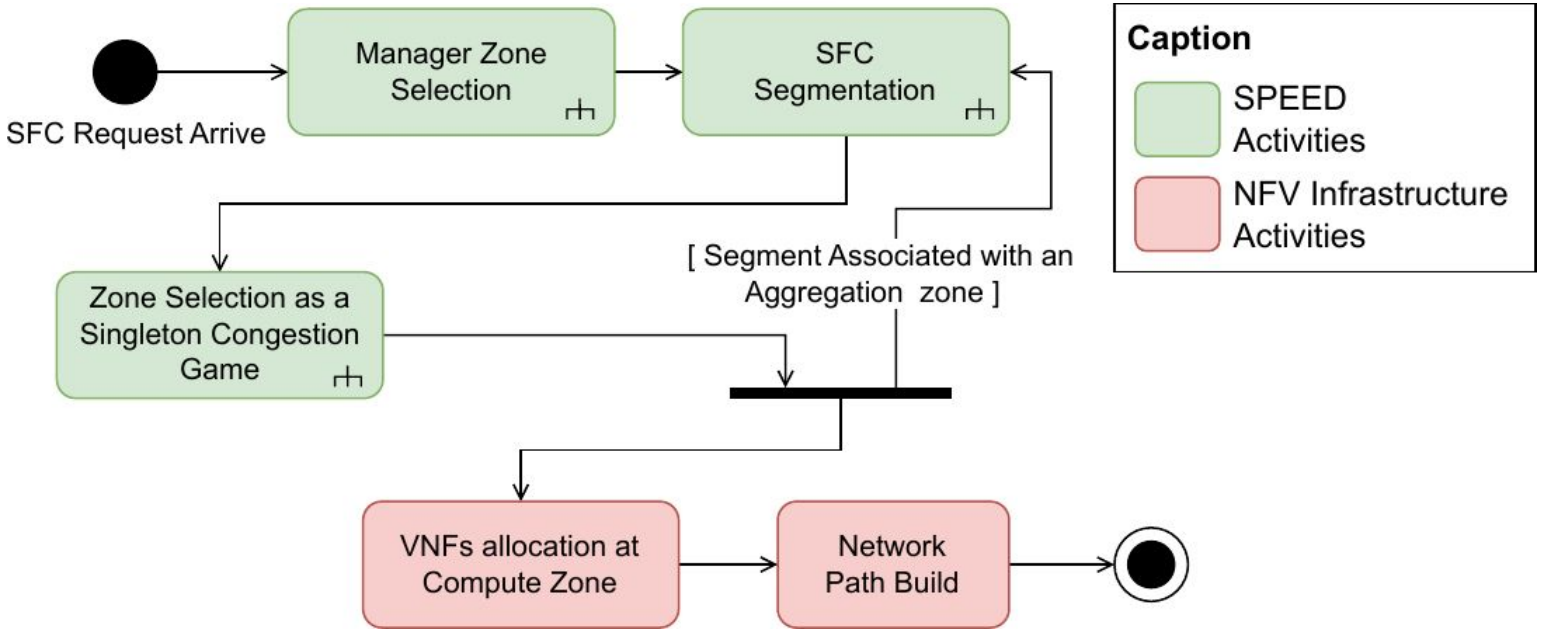
Zone	VNF	GW	Delay	Cost
C2	2	1	3	2
C2	3	1	3	1
C2	**4**	**1**	**3**	**1**

Architectural Components

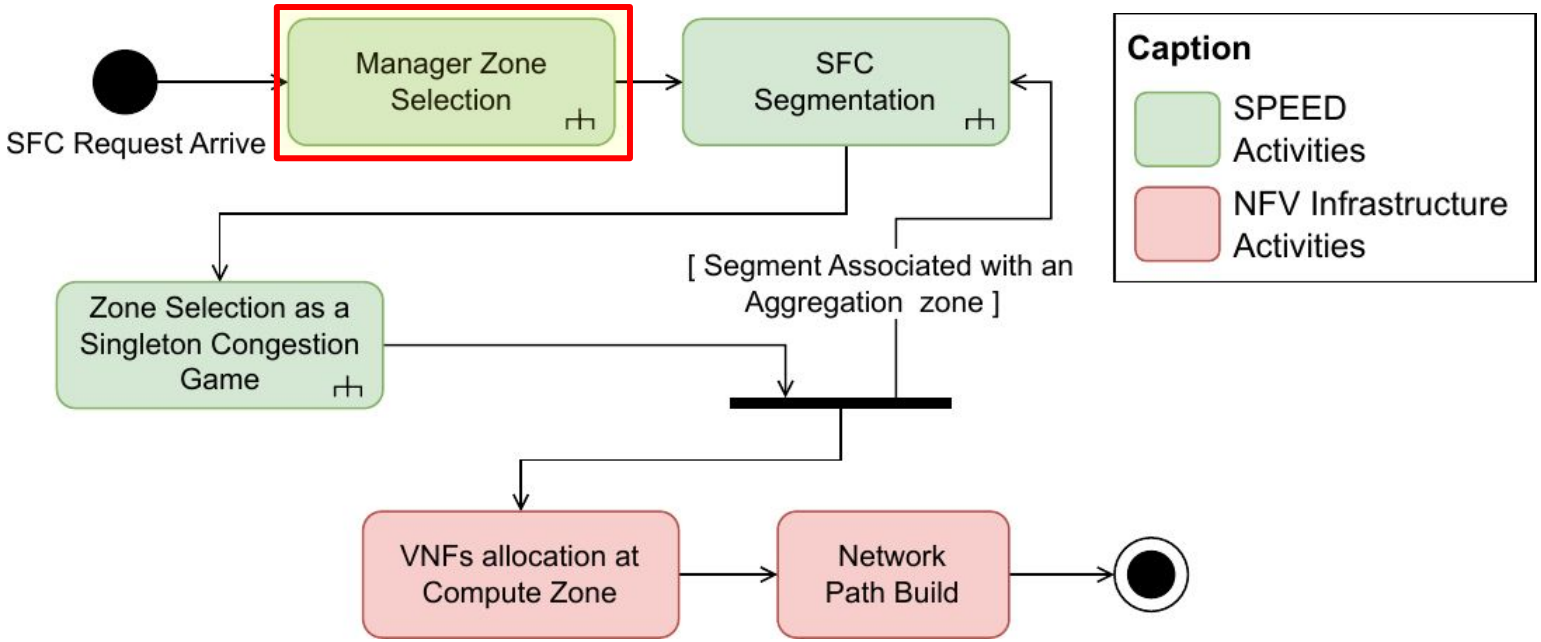
- **Integrated NFV Platform**
- **Aggregation zone** has **SPEED components**
- Each SFC is manage by one SPEED component
    - The **segments** can be manage by a **different zones**



SPEED Approach

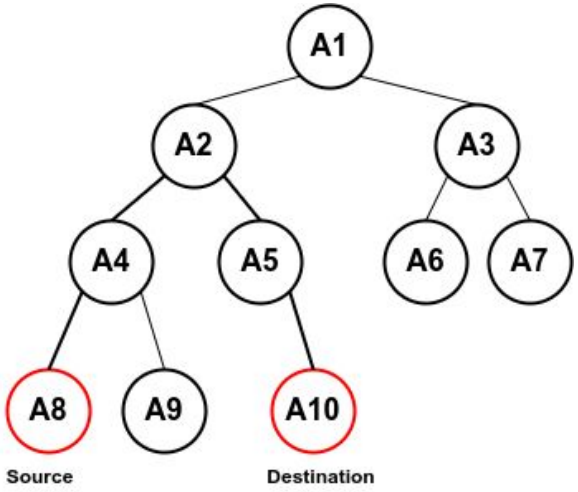


SPEED Approach - Manager Zone Selection

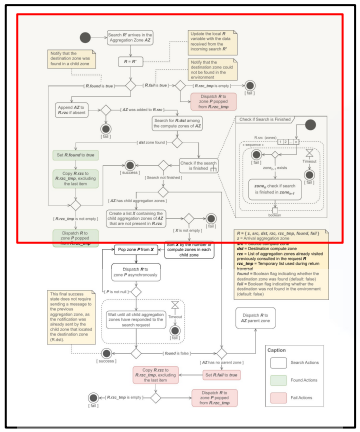


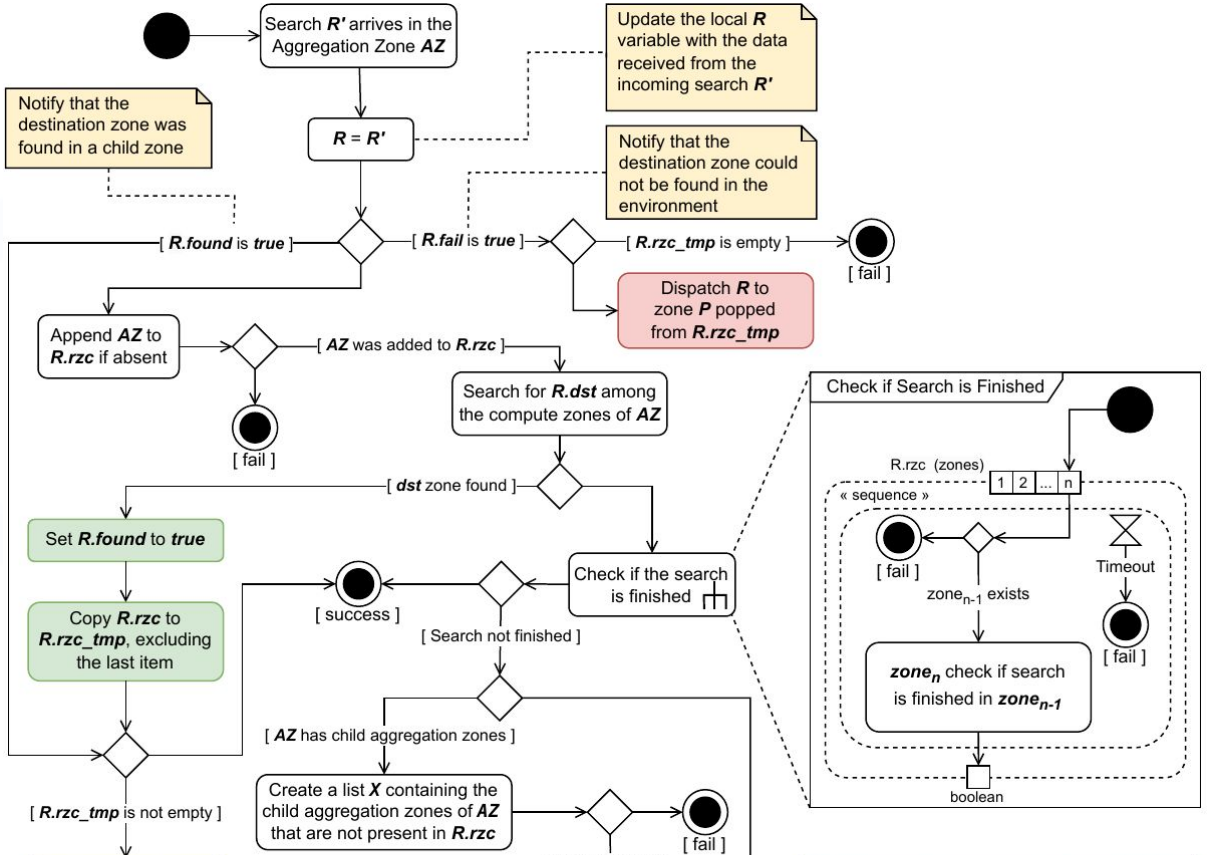
Manager Zone Selection

- The selected manager zone is required to comply with:
  a. Being the **closest common ancestor between source and destination**
  b. **All the VNF Types must be available** in a computed zone **underneath the selected manager zone**

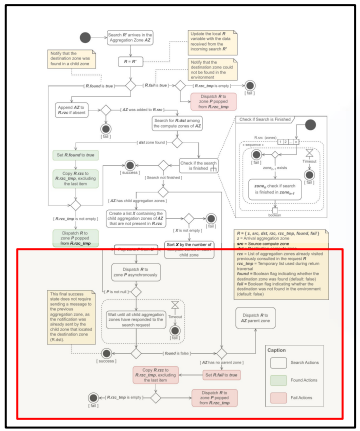


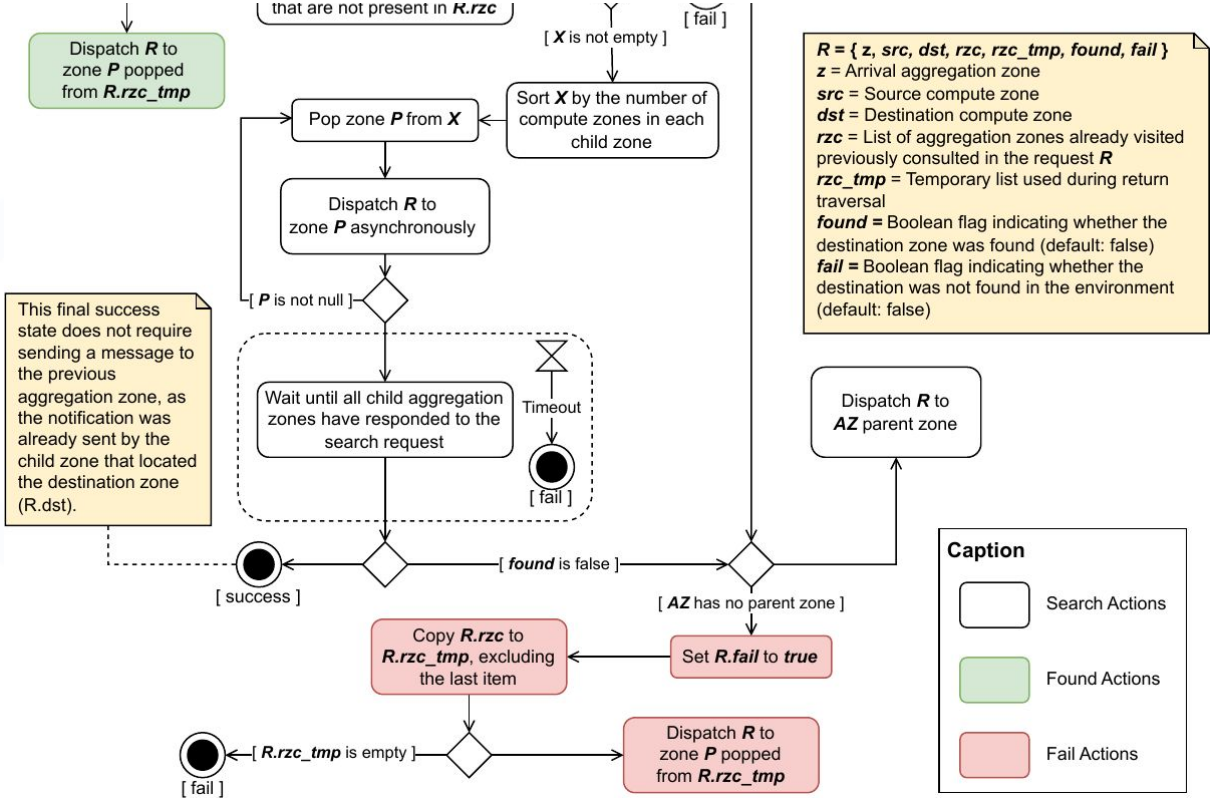
Manager Zone Selection (Distributed Deep First Search)



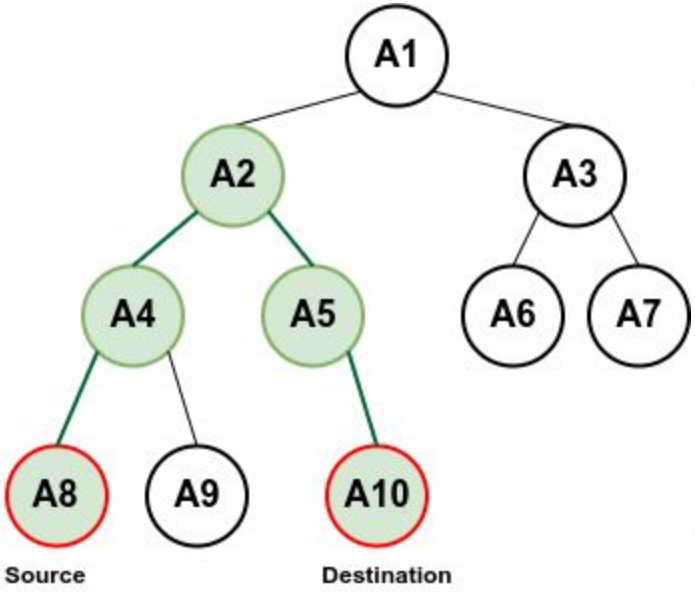


Manager Zone Selection (Distributed Deep First Search)

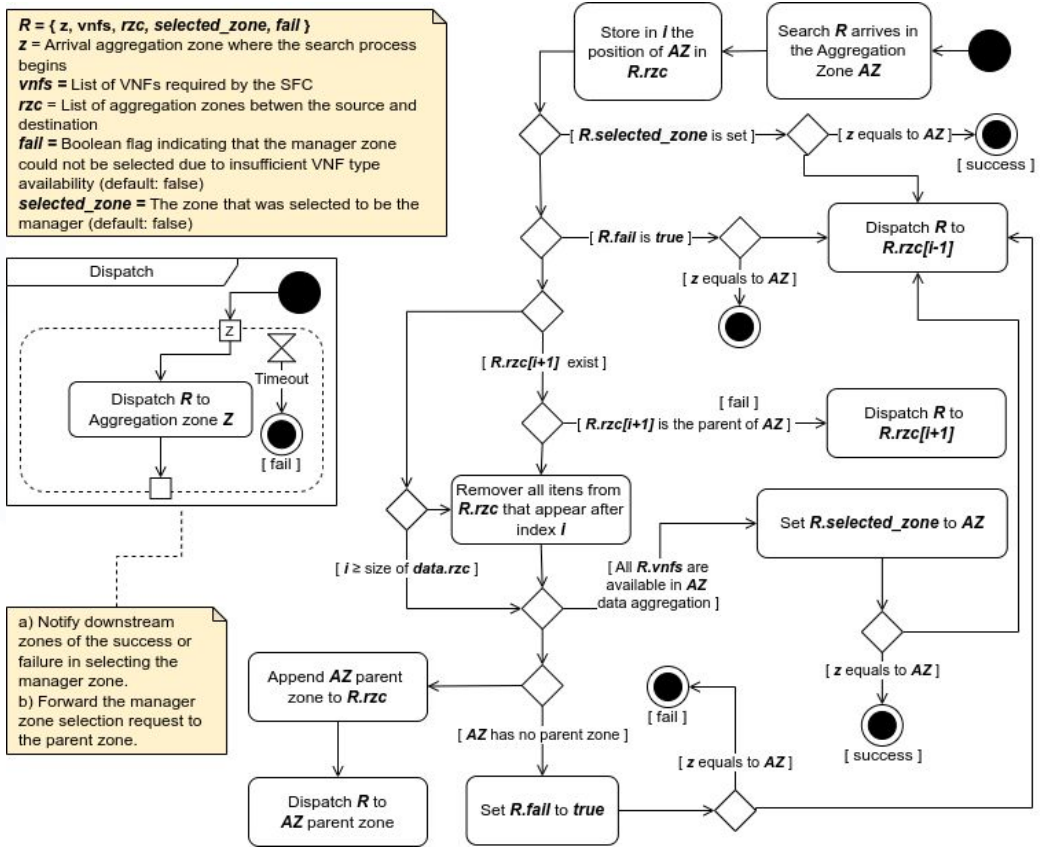




Manager Zone Selection (Distributed Deep First Search)



Manager Zone Selection



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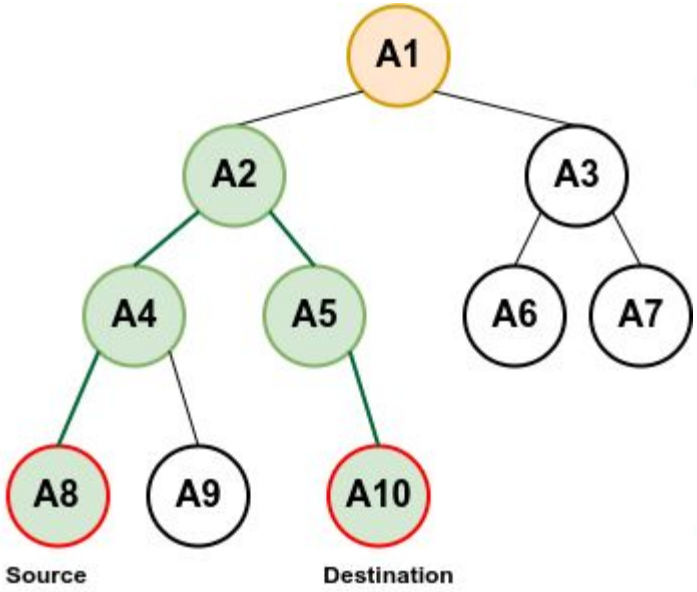
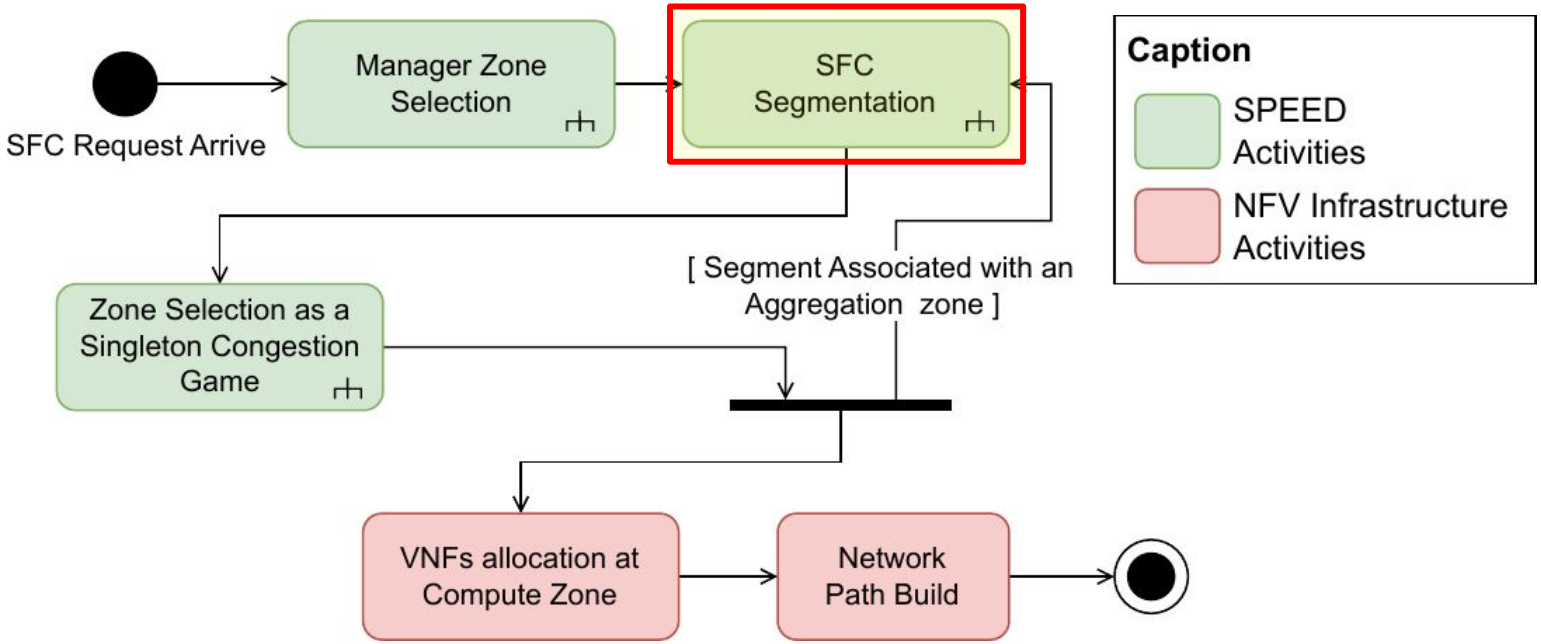
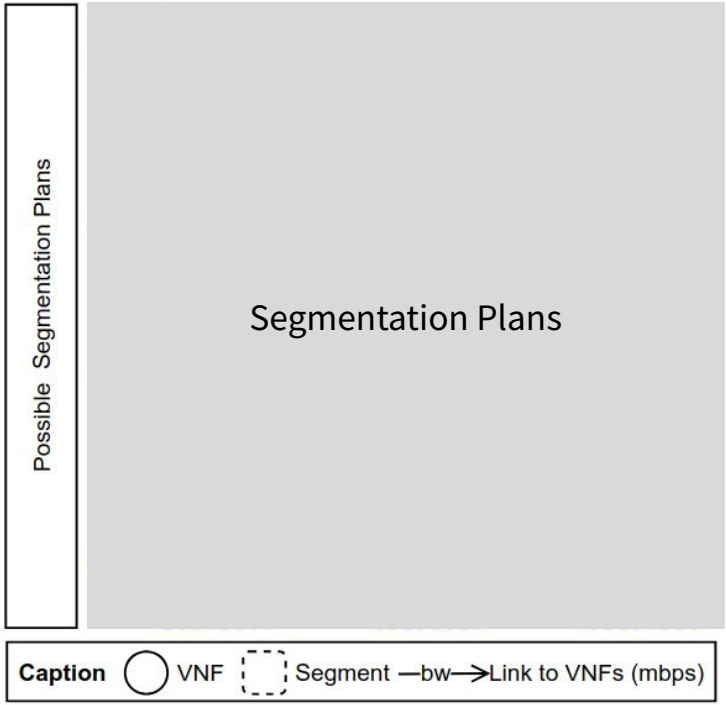


SPEED Approach - SFC Segmentation



SFC Segmentation

- **To execute an SFC in a multi-domain** environment, the SFC **must be segmented**
  - Segments are **portions of an SFC** that are confined within a single domain
- The **SFC segmentation** divides an SFC into **segments**



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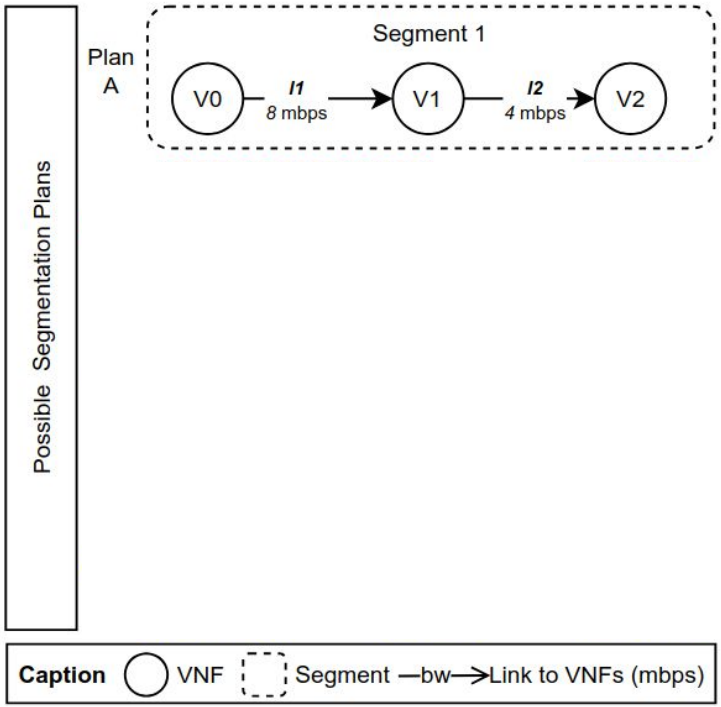

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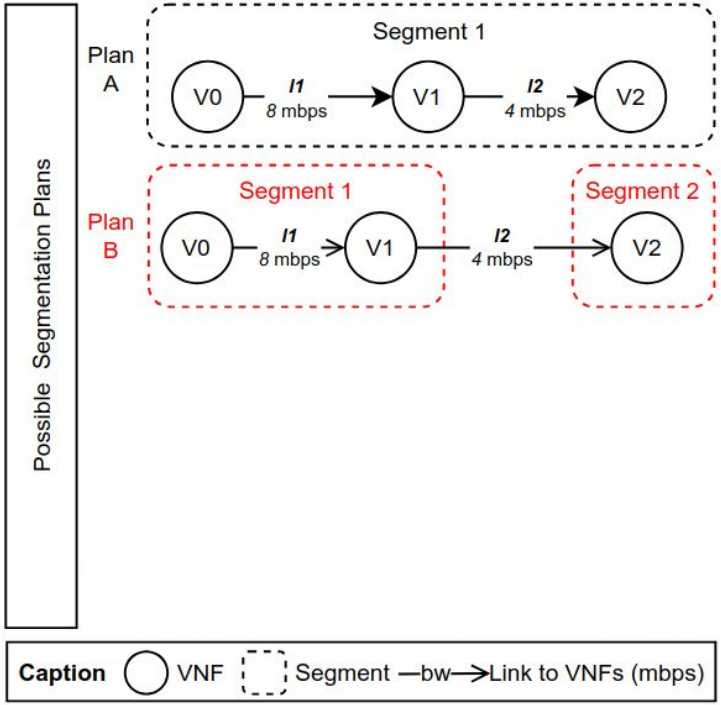

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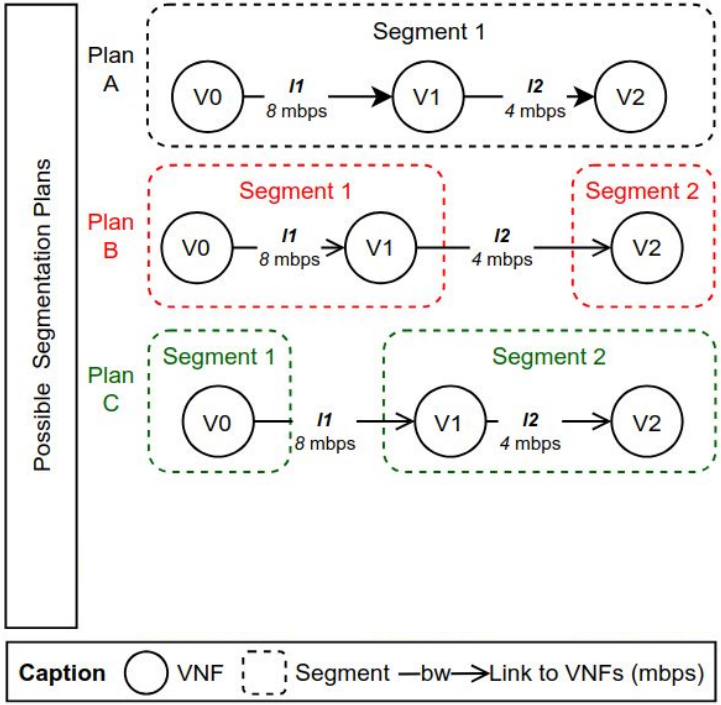

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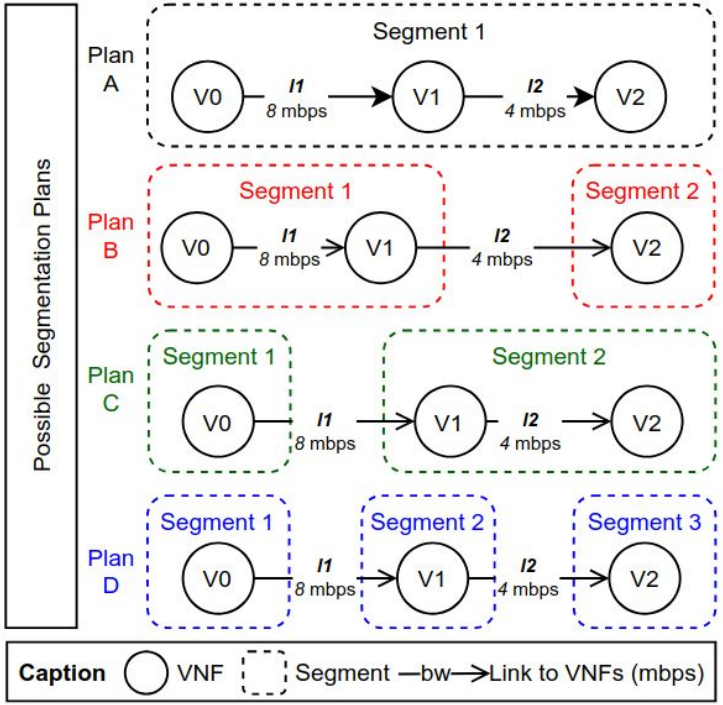
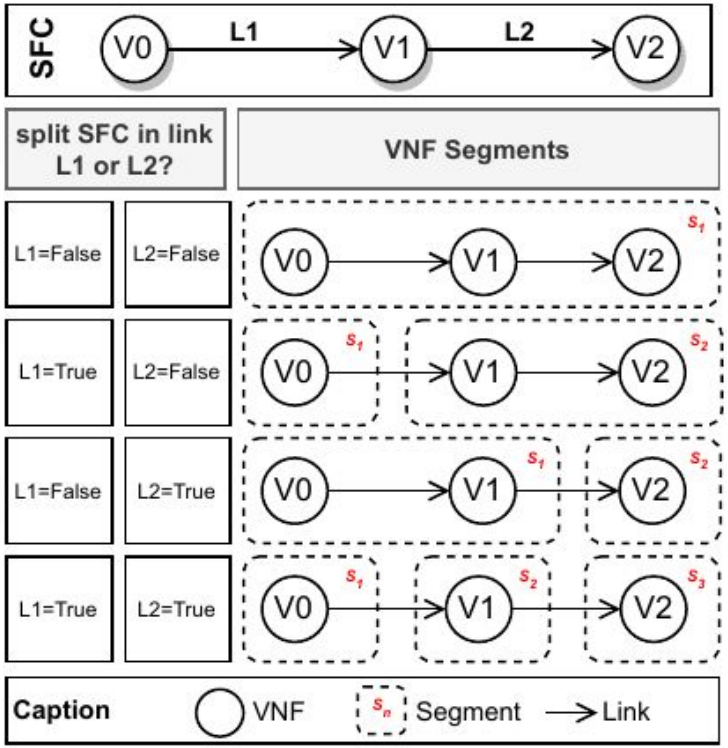
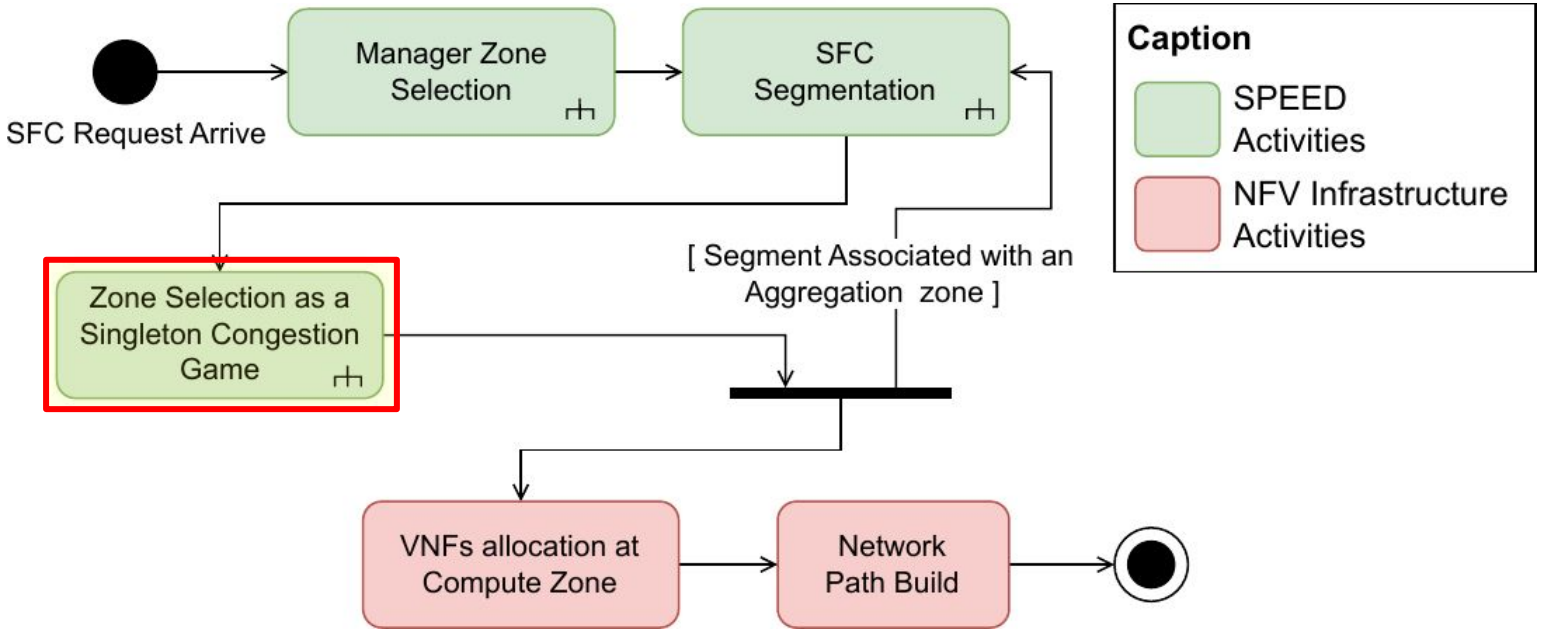


SFC Segmentation



SPEED Approach - Singleton Congestion Game (SGC)



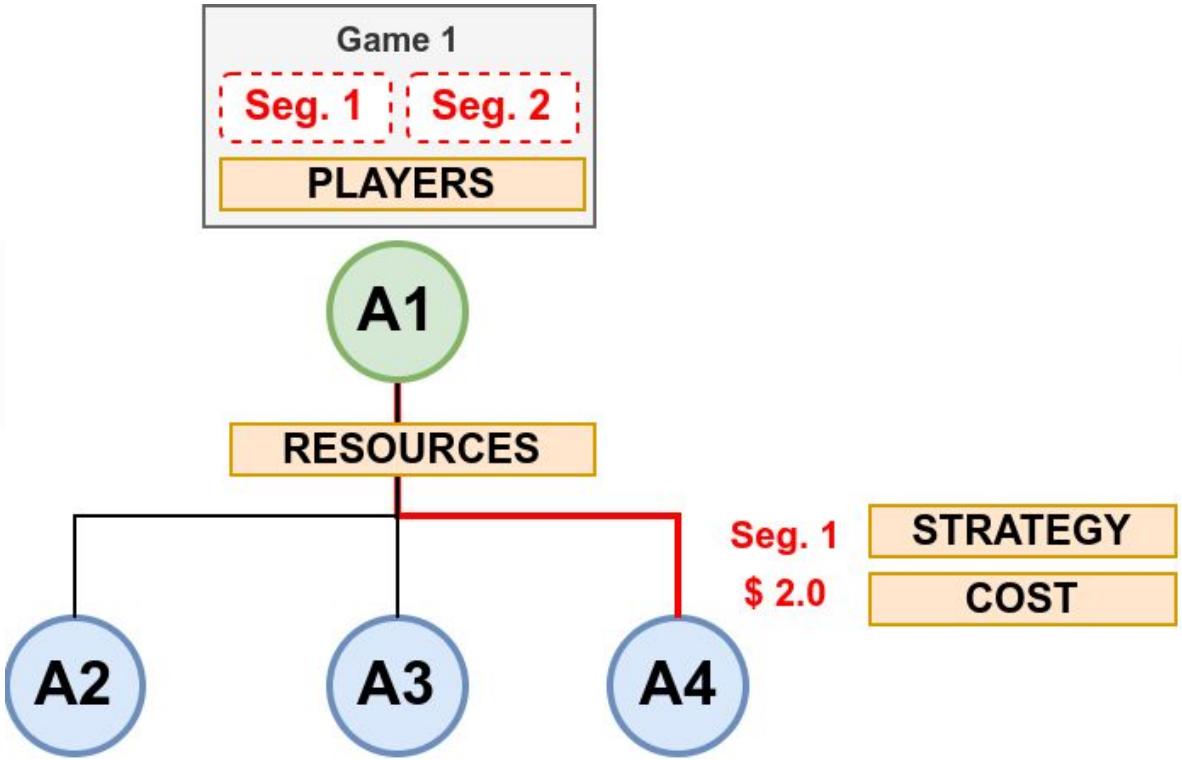
Mapping the SFC Placement Problem as a SCG

- **Game Theory** can be adopted in scenarios where multiple entities make strategic decisions, for example, leasing or not a resource, based on the behavior of the other entities
  - **Congestion game** is a class of games used to model situations in which players compete against each other for the same resources
    - In a **Singleton Congestion Game** all players must allocate a **single resource** from a subset of allowed resources

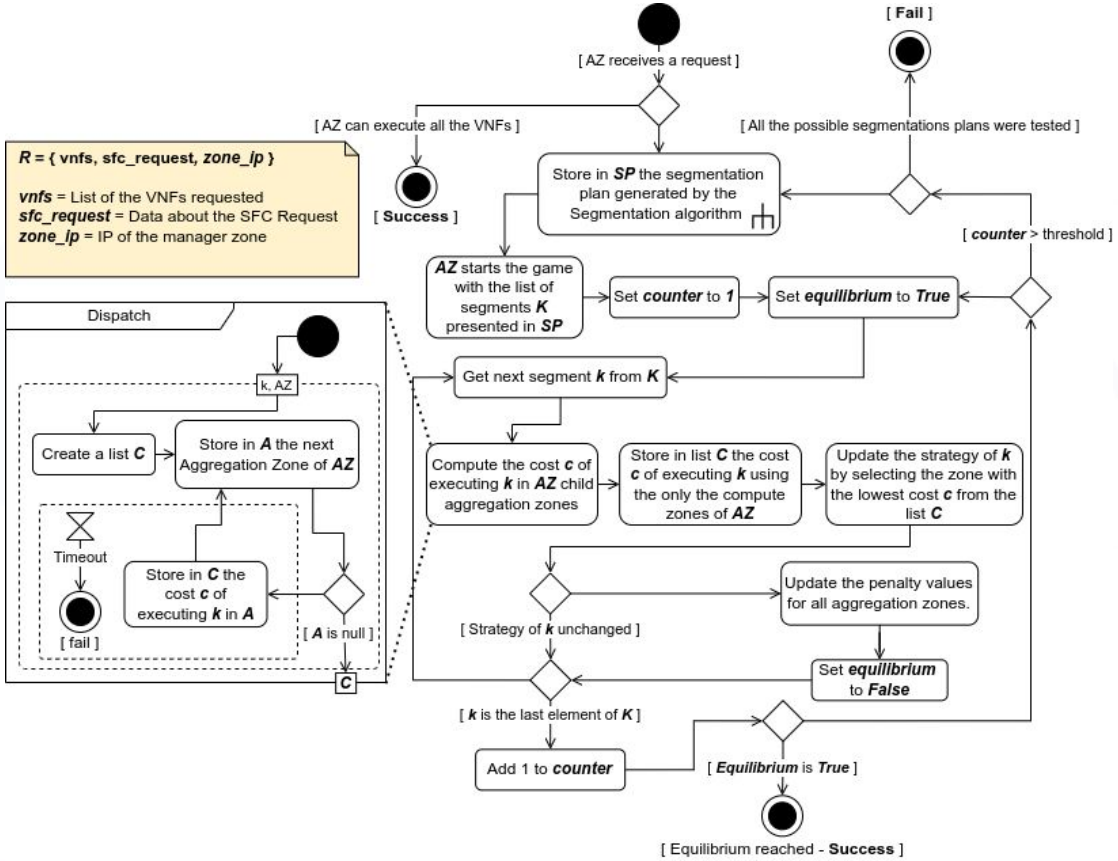
Mapping the SFC Placement Problem as a SCG

- The set of **players** is composed of **segments**
- The set of **resources** is composed of the **bind between the Aggregation** zone and its child zones
- The set of **strategies** that each player is the **graph's edges that connect the Aggregation zone** with the child zones
- The **cost function** is the cost of **executing the VNFs of the segment into a particular child zone**

Mapping the SFC Placement Problem as a SCG



Players Strategy Update



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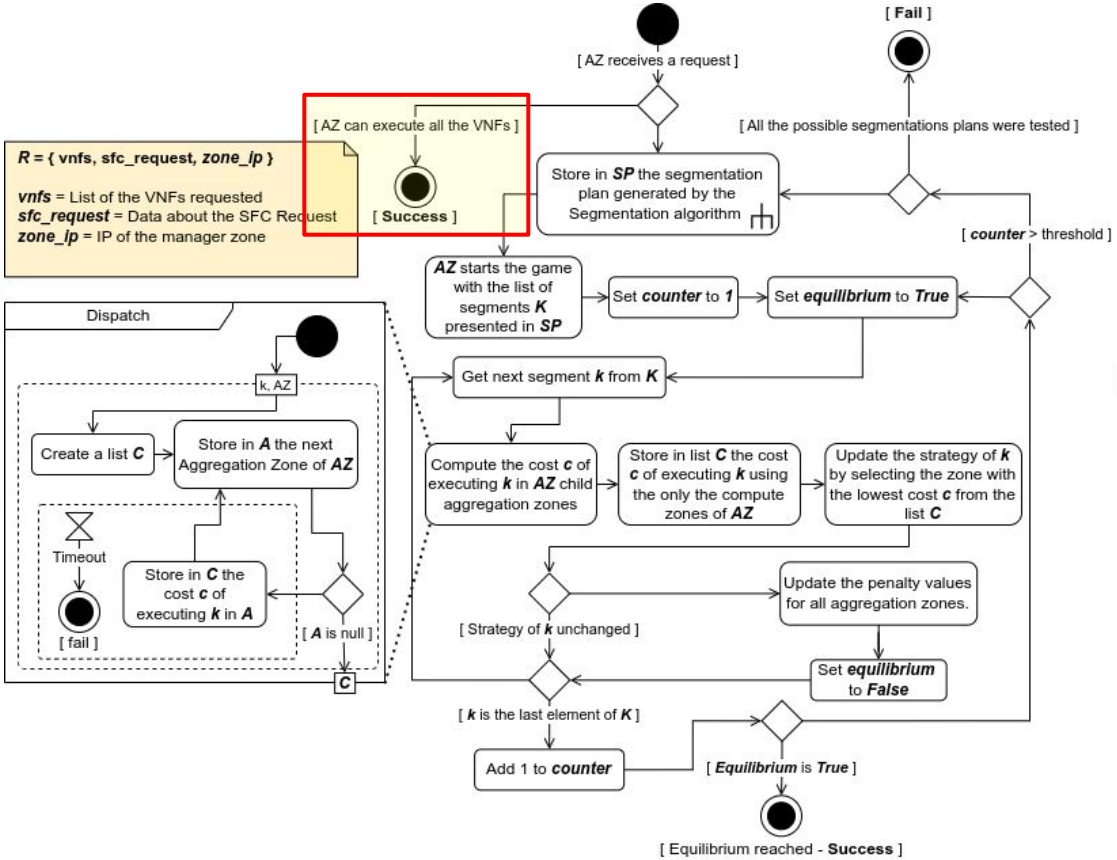
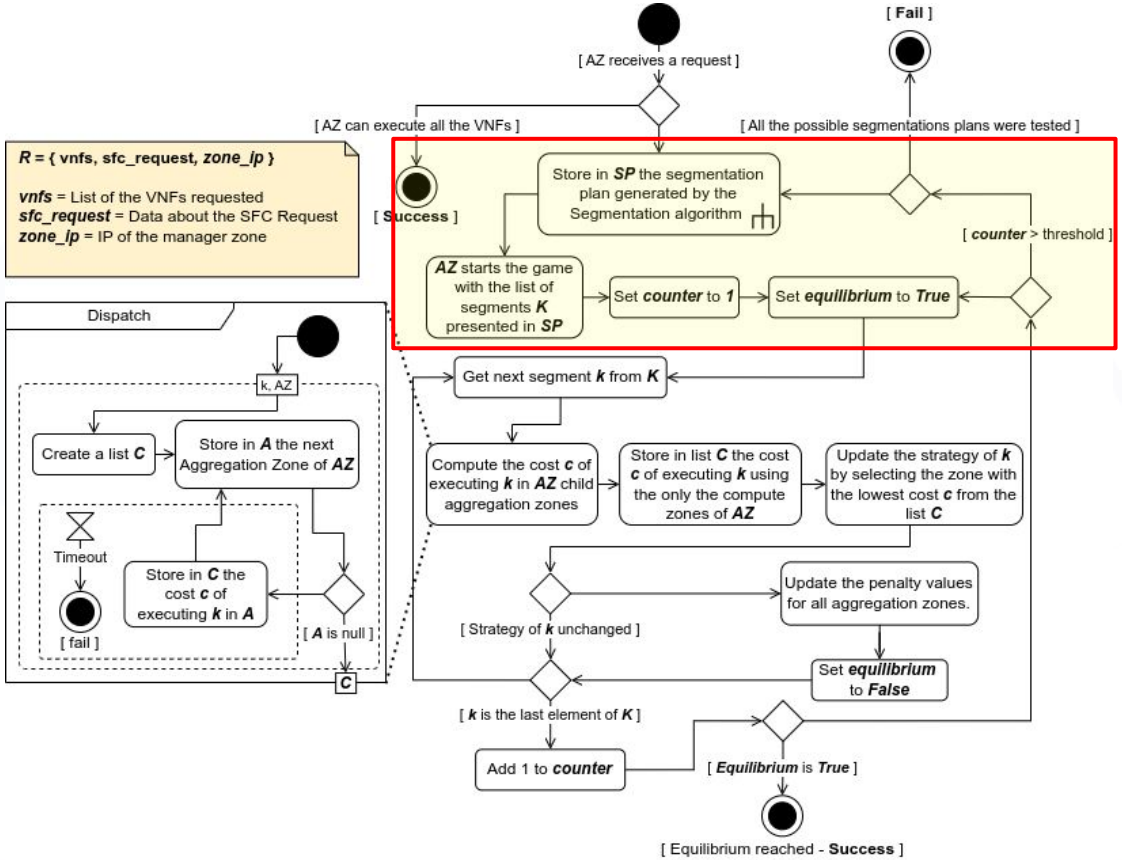


Players Strategy Update



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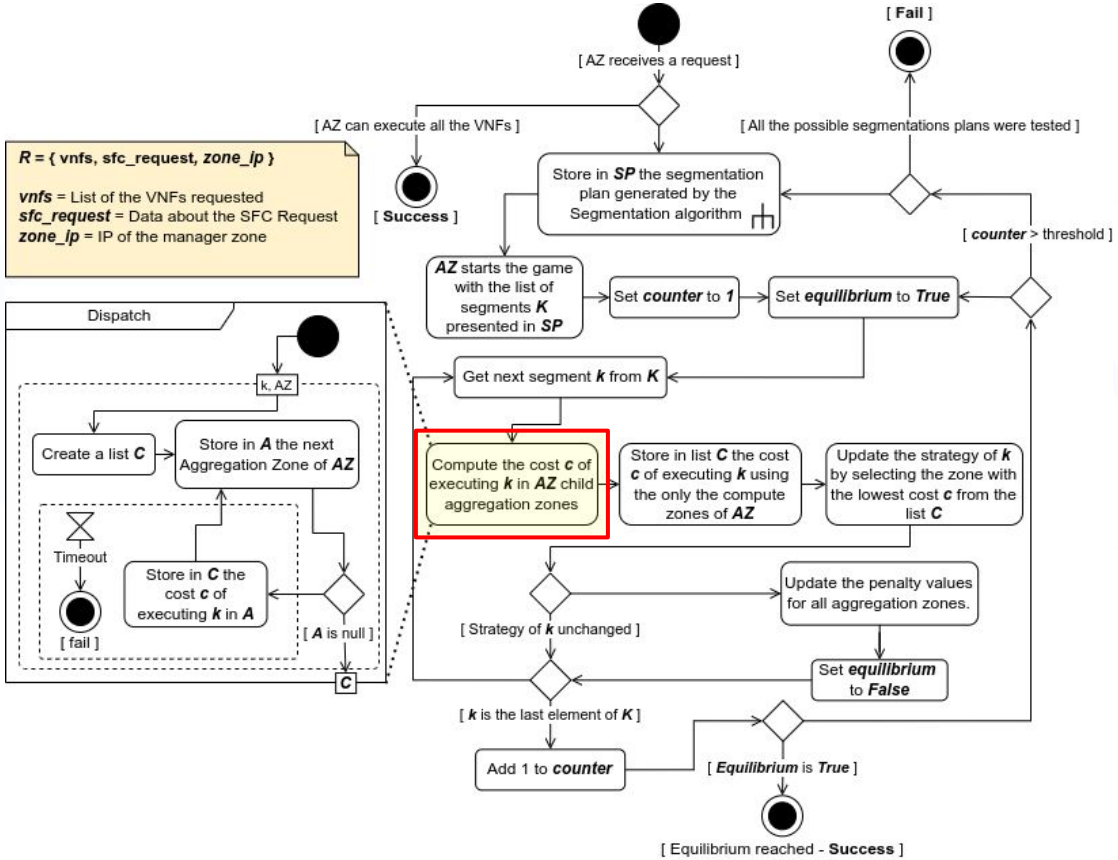

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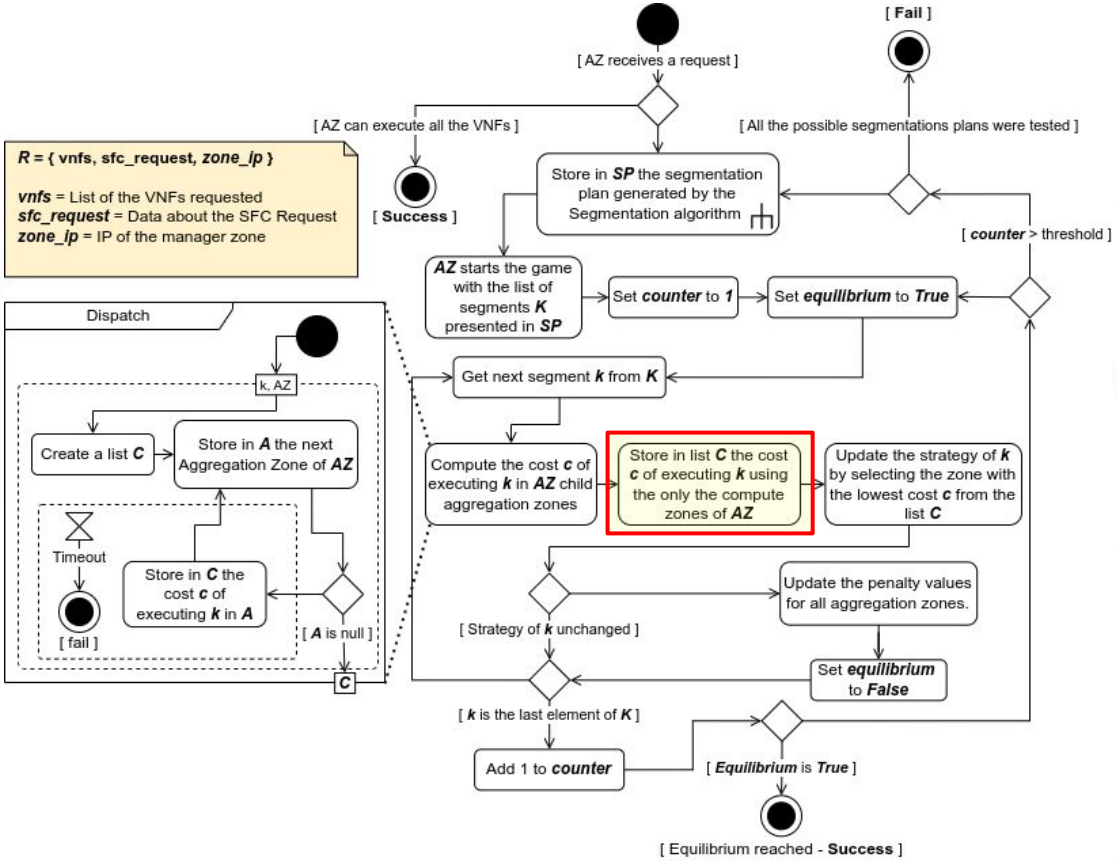

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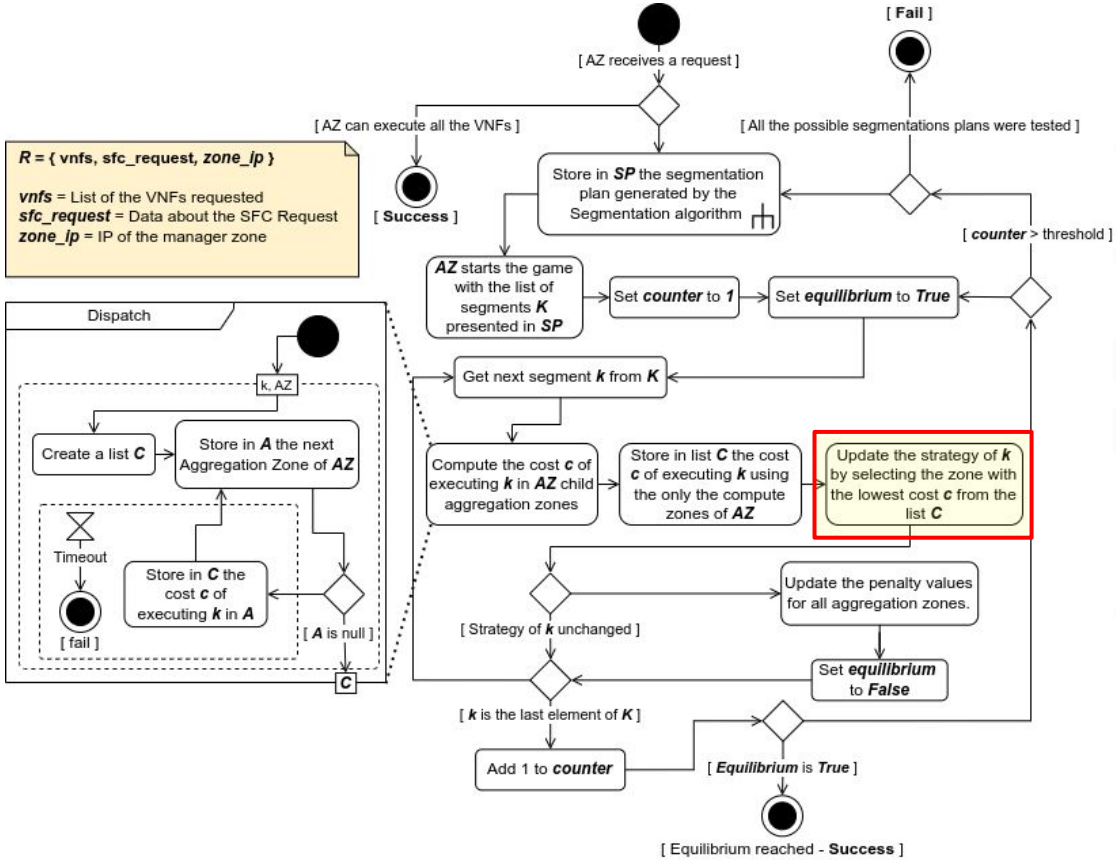
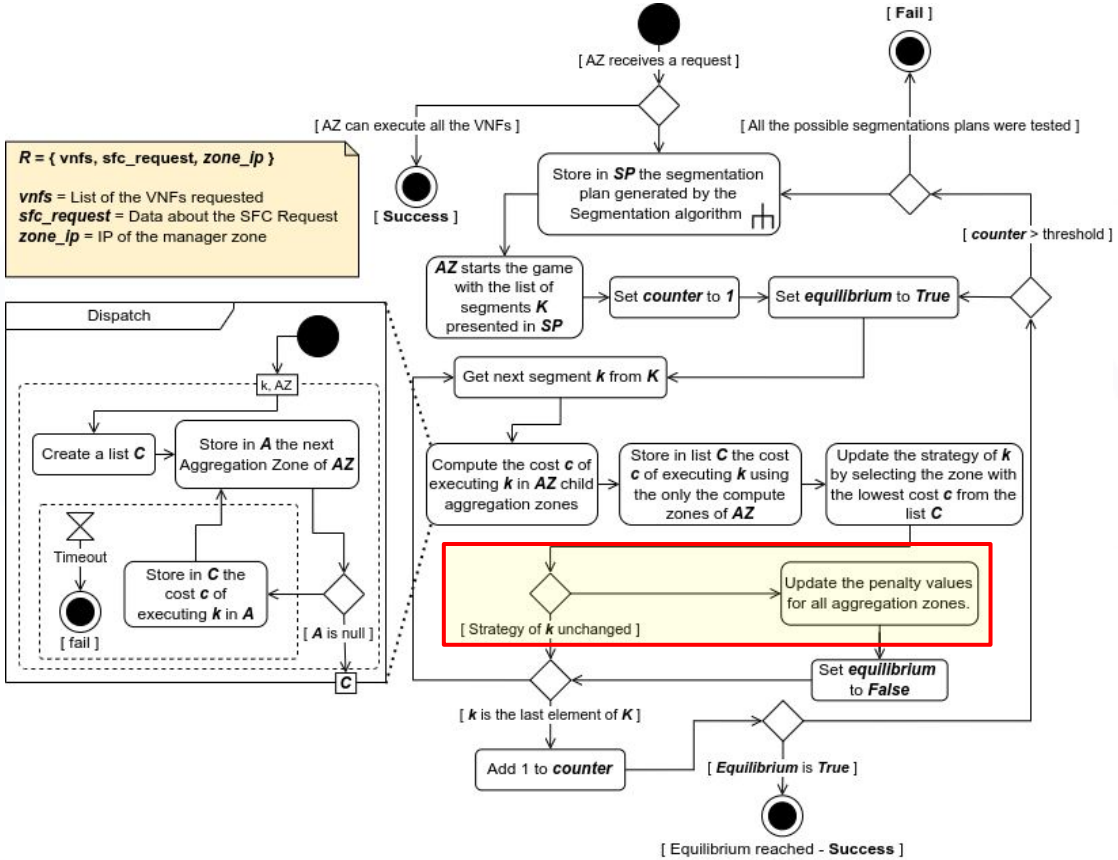


$$c(k_i, z) = \left(\sum_{f \in \mathcal{F}(k_i)} c_{\text{vnf}}(f, z) \right) \cdot penalty_z$$

$$penalty_z = \alpha \cdot e^{\beta n_z}$$

$$n_z = \sum_{k \in \mathcal{K}(z)} |\mathcal{F}(k)|$$

Players Strategy Update



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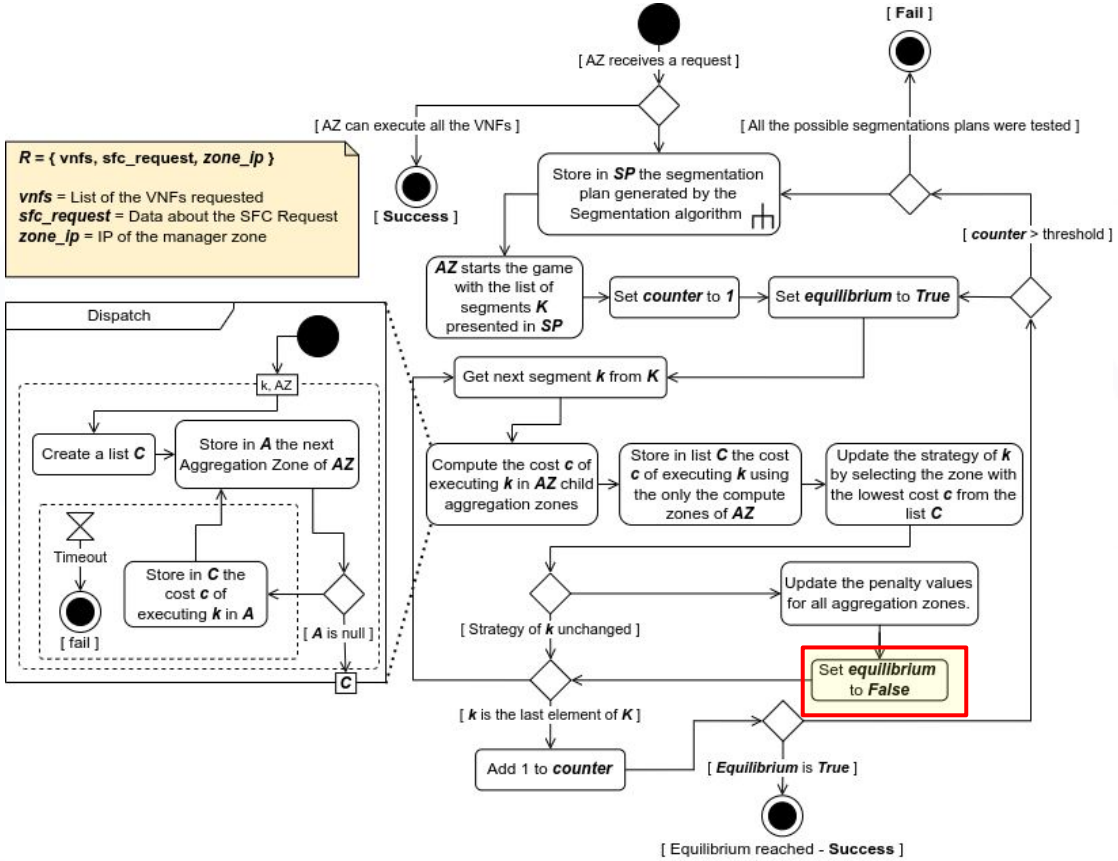

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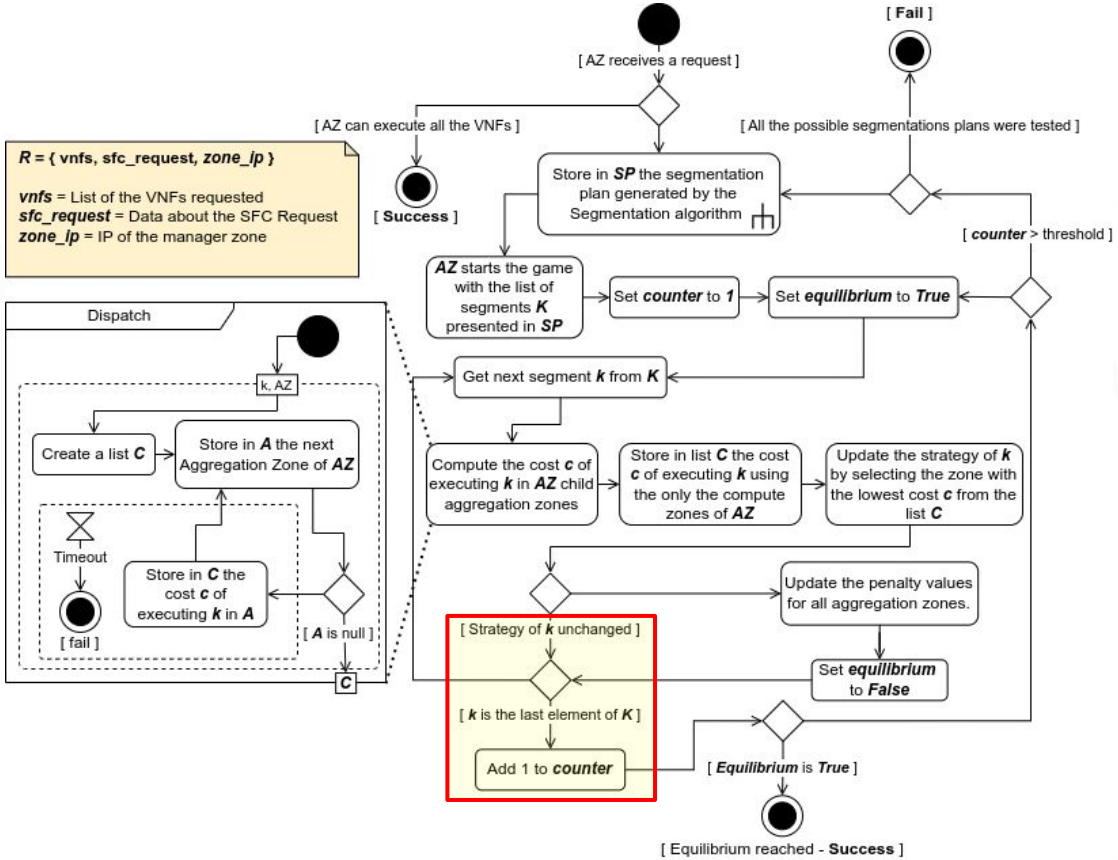

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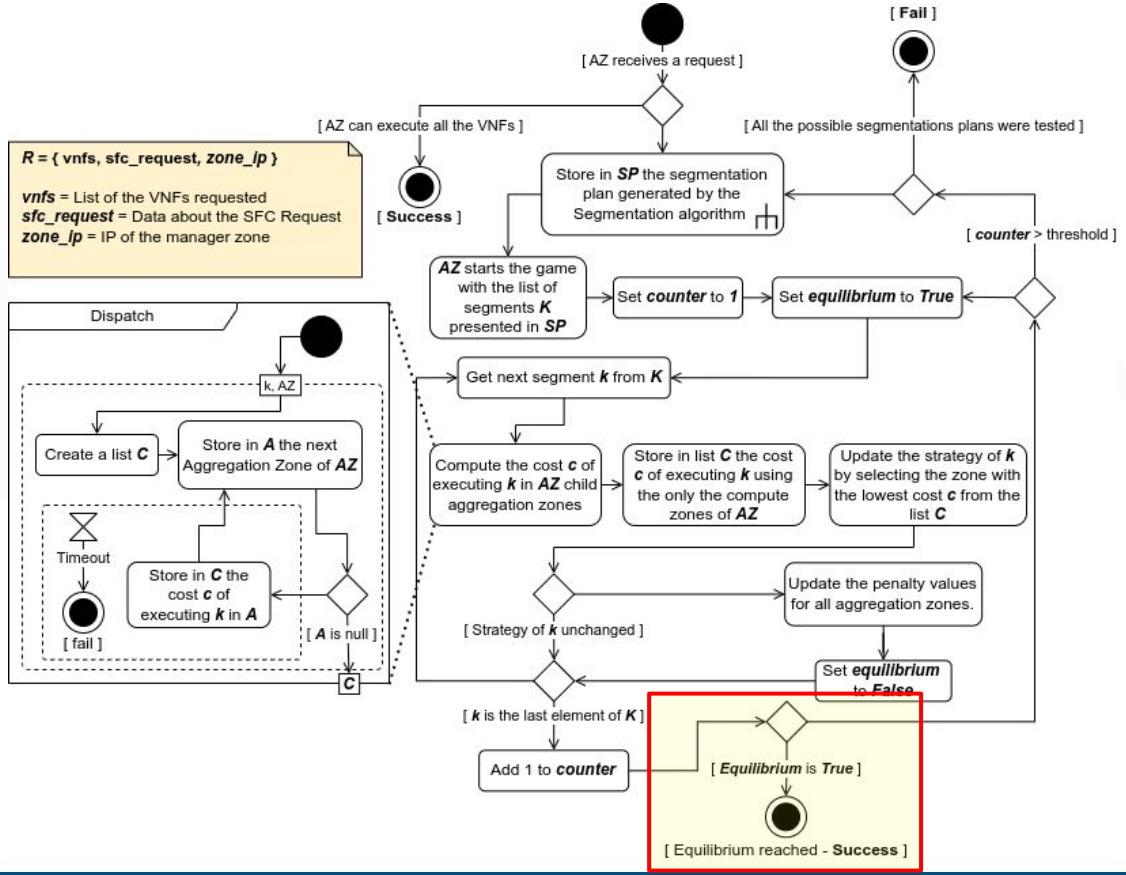

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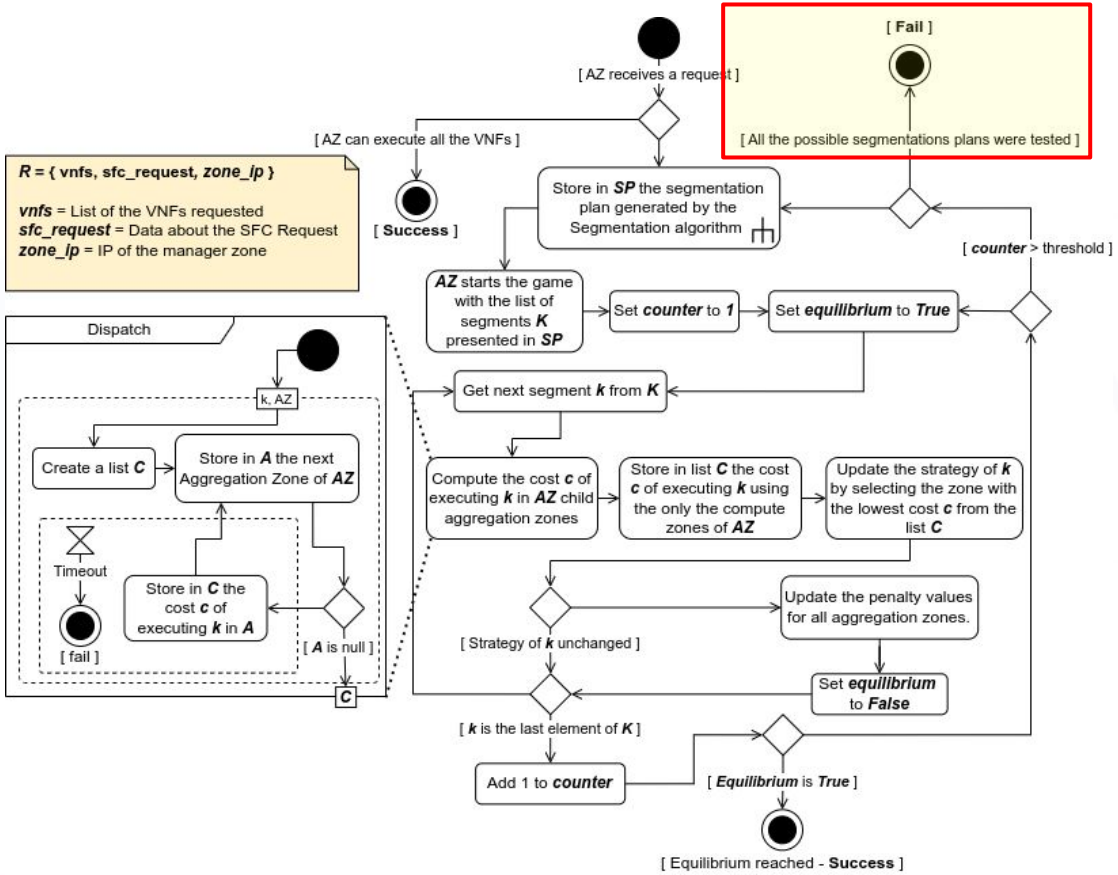


Game Execution With Penalty

Aggregated Data In Aggregation Zones (B)

A1

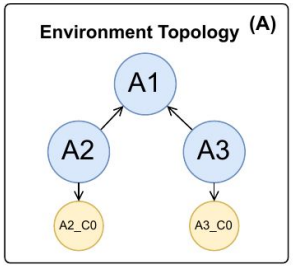

```
{
  "data": [
    {
      "zone": "A2",
      "vnfType": "vnf1",
      "cost": 1
    },
    {
      "zone": "A2",
      "vnfType": "vnf2",
      "cost": 1,
    }
  ]
}
```


A2


```
{
  "data": [
    {
      "zone": "A2_C0",
      "vnfType": "vnf1",
      "cost": 1
    },
    {
      "zone": "A2_C0",
      "vnfType": "vnf2",
      "cost": 1
    },
  ]
}
```


A3


```
{
  "data": [
    {
      "zone": "A3_C0",
      "vnfType": "vnf1",
      "cost": 2
    }
  ]
}
```

Segmentation Plan

seg1=[VNF1] seg2=[VNF2]

Iteration	Zone	Segment	Cost	Penalty
1	A2	seg1	1	2
1	A2	seg2	1	4

Game Execution With Penalty

Aggregated Data In Aggregation Zones (B)

A1


```
{
  "data": [
    {
      "zone": "A2",
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      "cost": 1
    },
    {
      "zone": "A2",
      "vnfType": "vnf2",
      "cost": 1,
    }
  ]
}
```
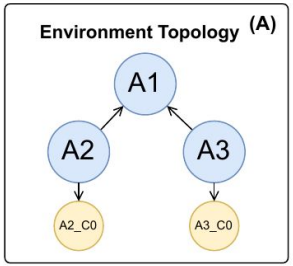


A2


```
{
  "data": [
    {
      "zone": "A2_C0",
      "vnfType": "vnf1",
      "cost": 1
    },
    {
      "zone": "A2_C0",
      "vnfType": "vnf2",
      "cost": 1
    },
  ]
}
```


A3


```
{
  "data": [
    {
      "zone": "A3_C0",
      "vnfType": "vnf1",
      "cost": 2
    }
  ]
}
```

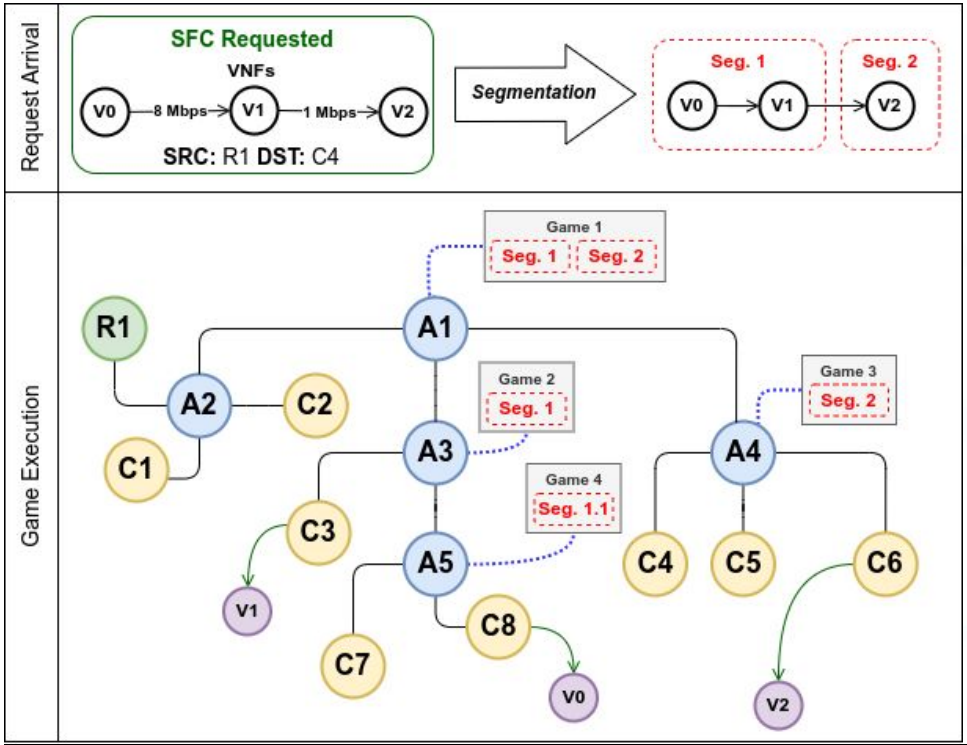



Segmentation Plan

seg1=[VNF1] seg2=[VNF2]

Iteration	Zone	Segment	Cost	Penalty
1	A2	seg1	1	2
1	A2	seg2	1	4
2	A3	seg1	2	2
2	A2	seg2	1	2

Zone Selection as a Singleton Congestion Game



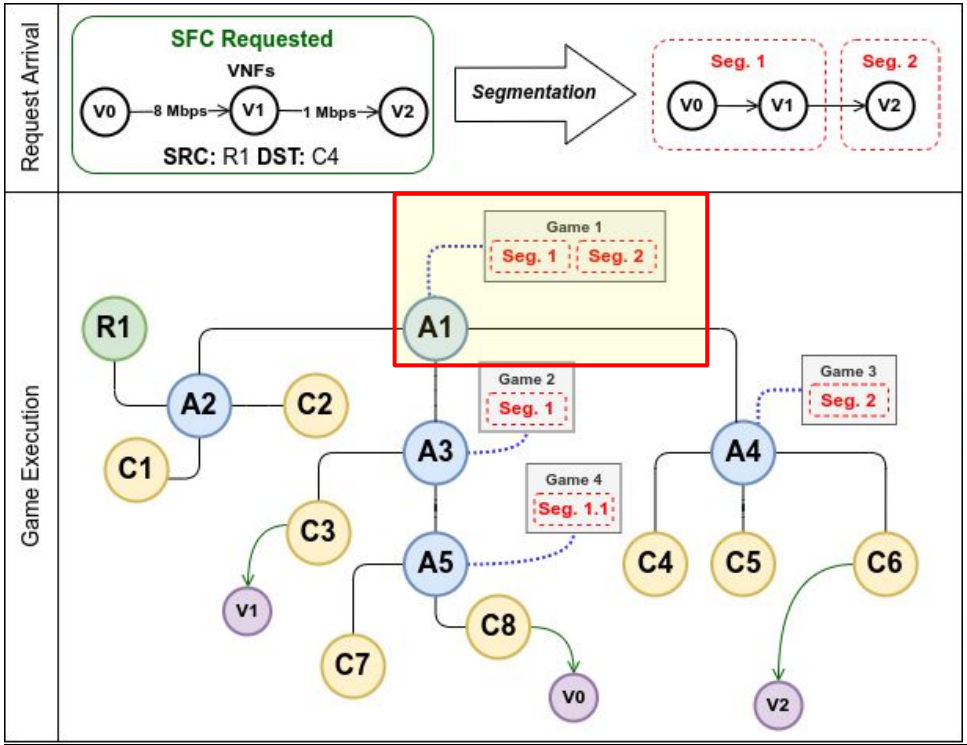
Games	Segmentation Plans
Game 1 in A1 — Seg. 1, Seg. 2	Seg. 1 (V0 → V1), Seg. 2 (V2)
Game 2 in A3 — Seg. 1.1, Seg. 1.2	Seg. 1.1 (V0), Seg. 1.2 (V1)
Game 3 in A4 — Seg. 2	Seg. 2 (V2)
Game 4 in A5 — Seg. 1.1	Seg. 1.1 (V0)

Caption

Access zone · Compute zone · Aggregation zone · VNF Description · VNF Instance · SFC Requested · Segments · Game

Game Execution · VNF Placed · Hierarchical Topology

Zone Selection as a Singleton Congestion Game



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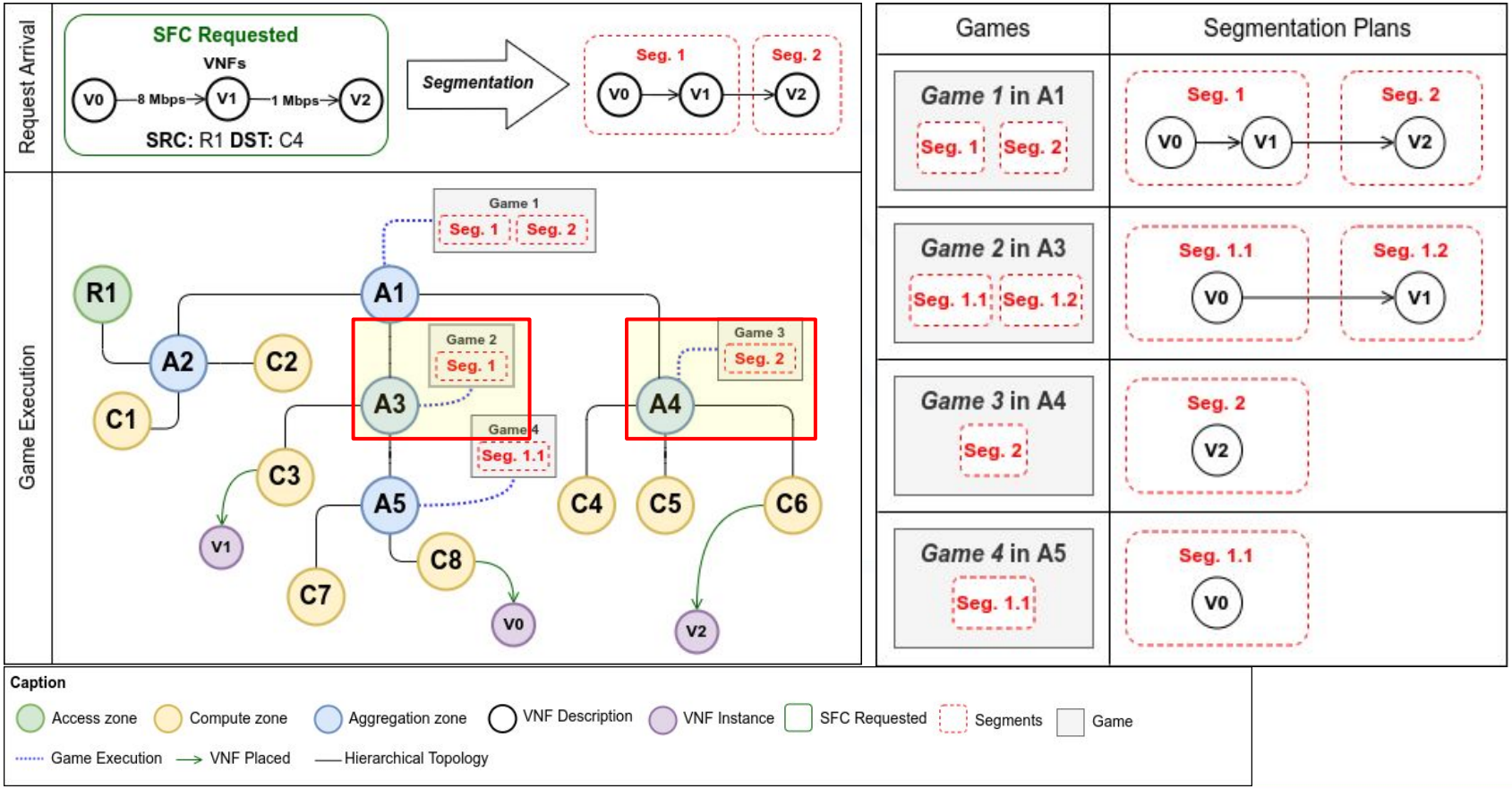

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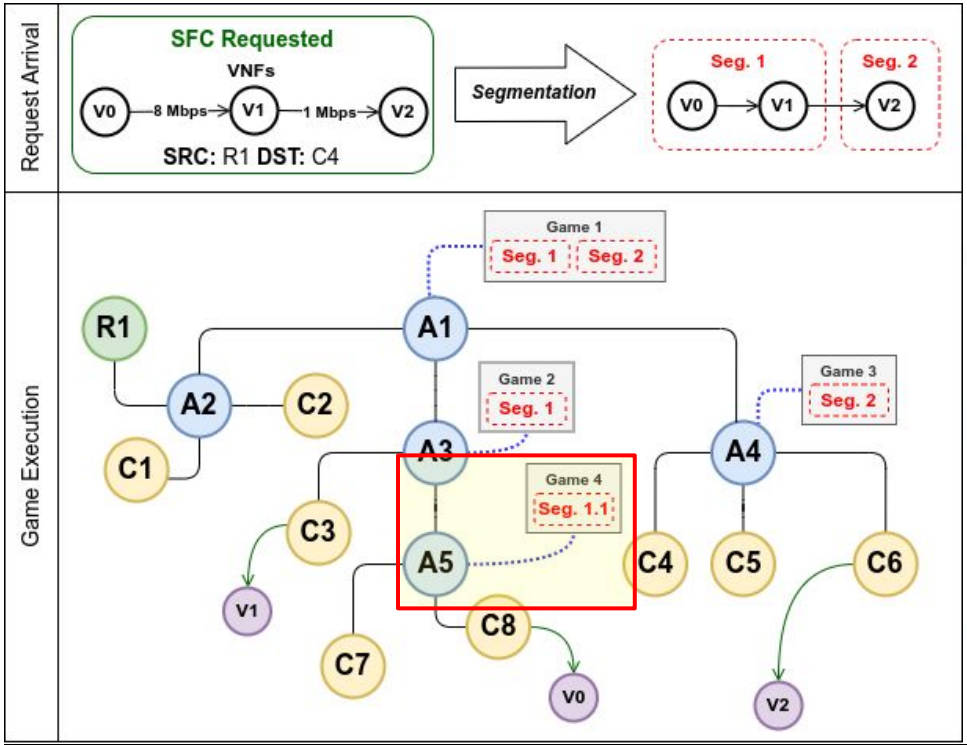

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Evaluation

- Simulated Environment
- Real Environment

Evaluation Goals and Metrics

- Evaluate if the proposed solution
  a. Reduces the monetary cost of the SFC execution
  b. Increases the SFC Placement success rate
- In the real environment we also validate the overhead produced by our proposed solution

Simulation Environment

- **We build our simulation**
  - **SimPy** is a process-based discrete-event simulation
- **Source Code**
  - https://github.com/anselmobattisti/speed
  - https://github.com/anselmobattisti/speee_api

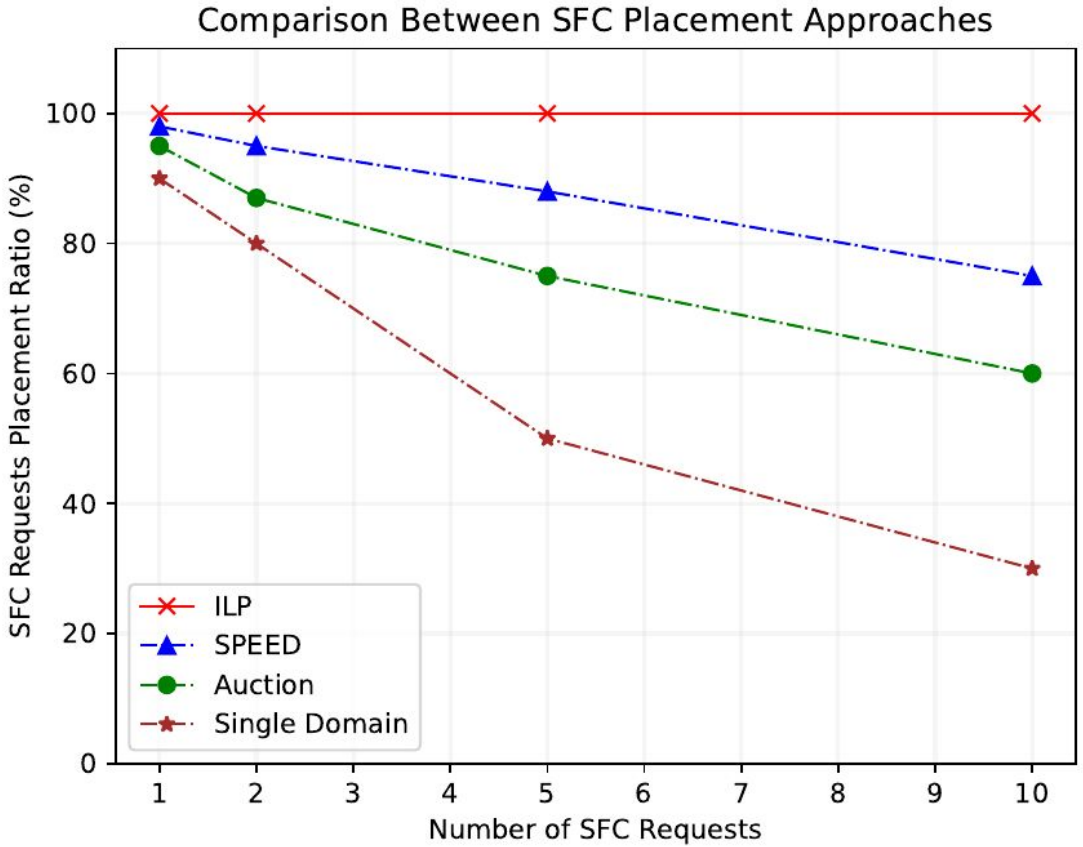
Simulation Environment

Description	Values
Number of Domains	64
Compute Nodes in Domain	[5,10]
CPU capacity	[1,5] GHz
Memory capacity	[1,5] GB
Bandwidth capacity in inter-domain link	1000 Mbps
Bandwidth capacity in intra-domain link	2000 Mbps
Link Delay	[2, 5] ms

Description	Values
CPU Cost	[0.001, 0.005] $/s
Memory Cost	[0.001, 0.004] $/GBs
CPU demand of VNF	[1,4] GHz
Memory demand of VNF	[1,5] GB
Traffic rate requirement	[100, 500] kbps
Traffic routing cost parameter	[0.02, 0.05] $/Mb
Maximum tolerated delay	[0, 50] ms

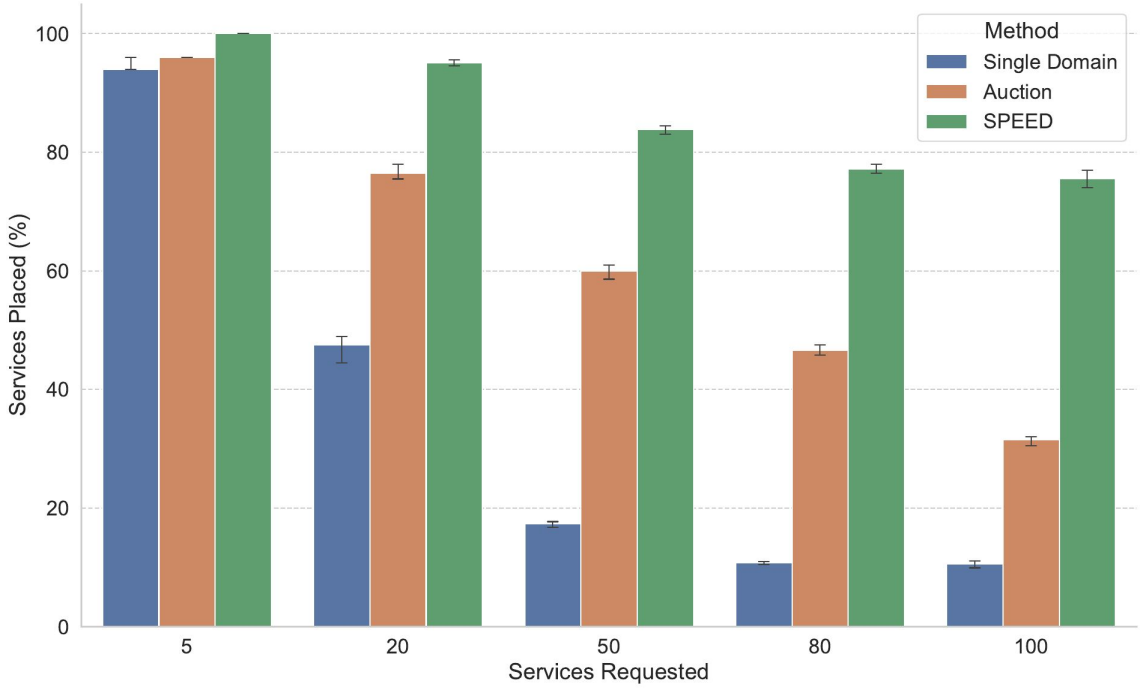
SFC Placement Success Rate

Evaluate the SFC Placement success rate of the proposed solution relative to an exact baseline



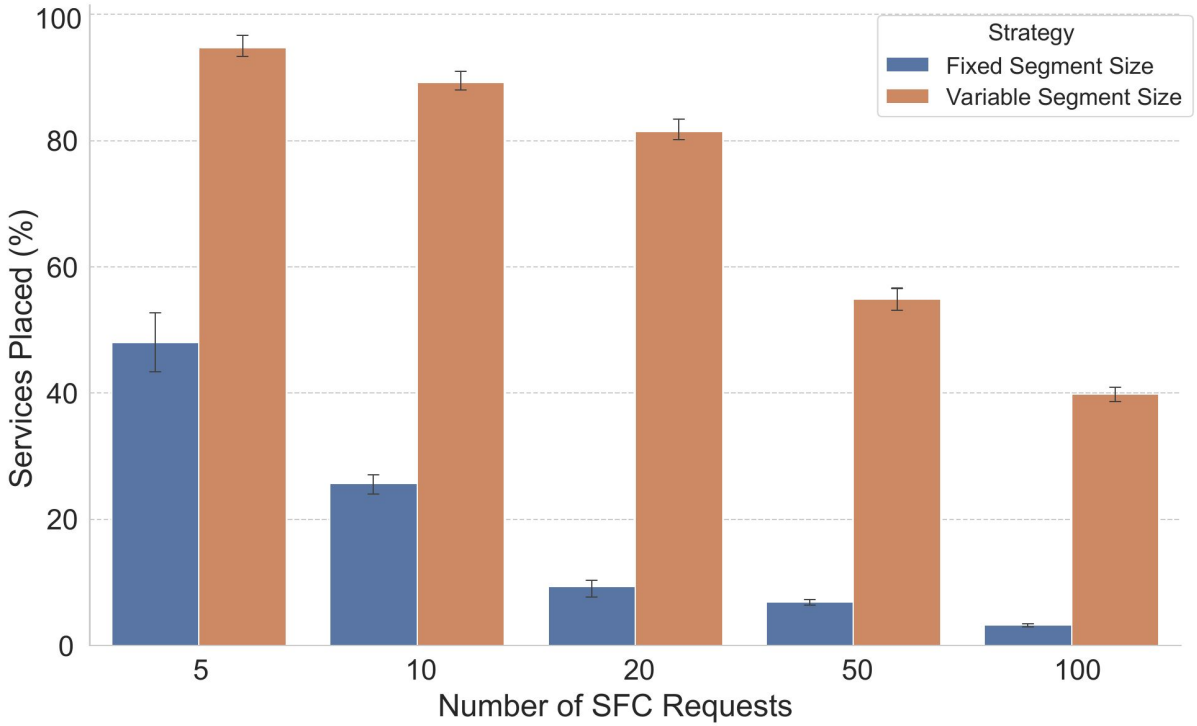
SFC Placement Success Rate

Evaluate the SFC Placement success rate of the proposed solution relative to other approaches with a bigger scenario



Impact of Segment Size on SFC Placement Success Rates

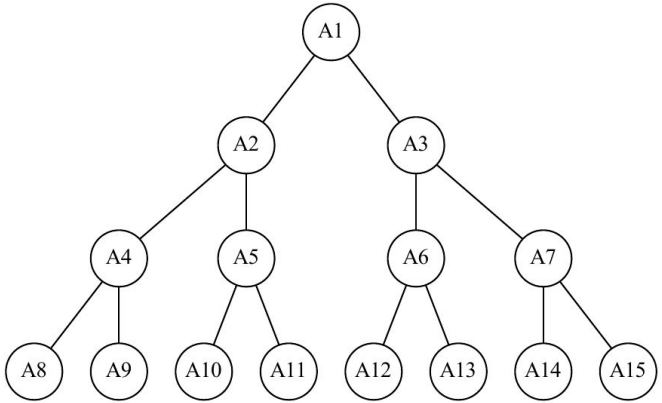
Assess whether adopting a variable segmentation size strategy increases the success rate of SFC placement

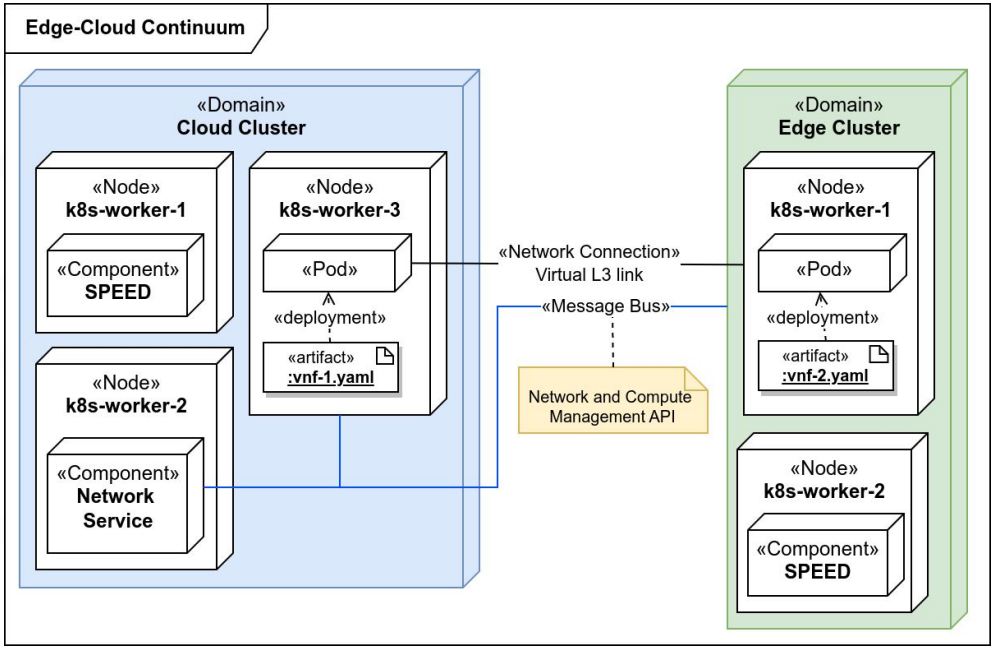


Evaluation

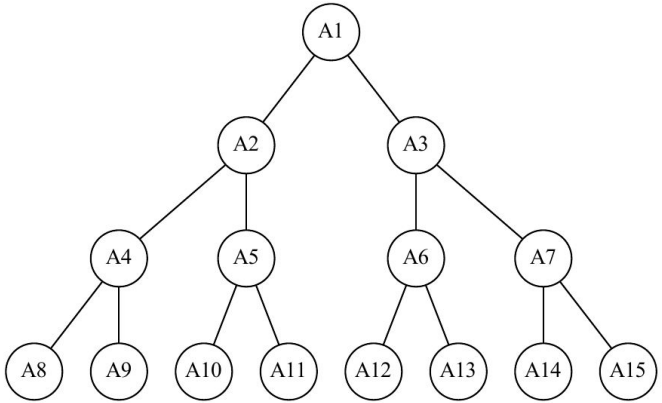
- Real Environment

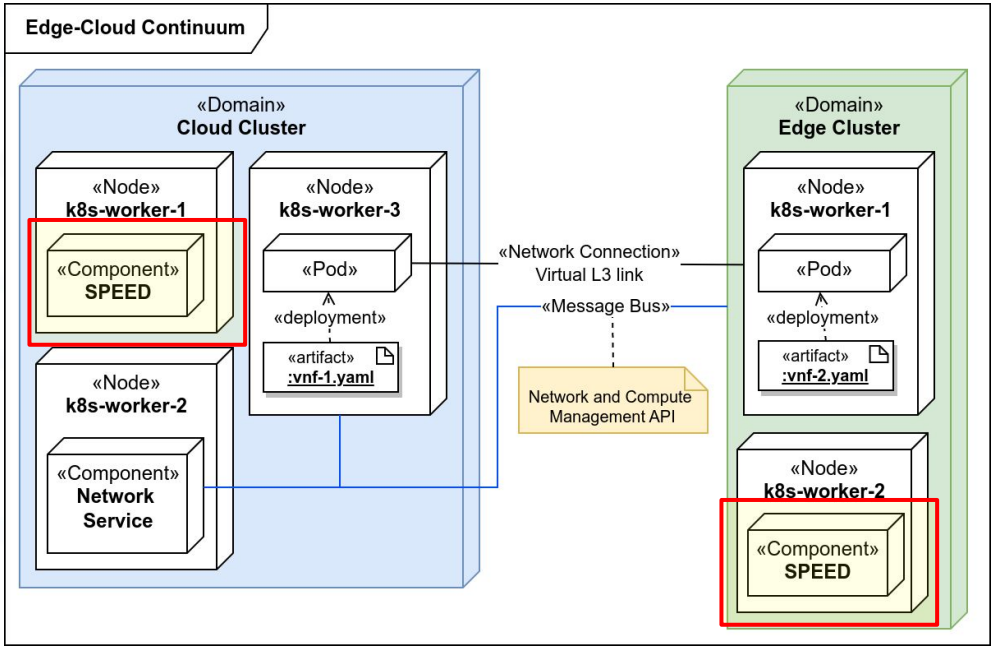
Real Environment





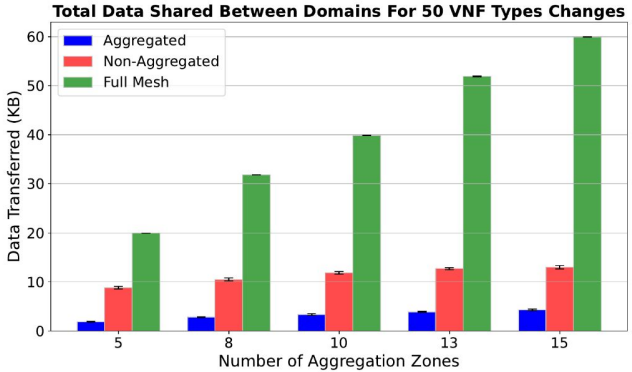
Real Environment

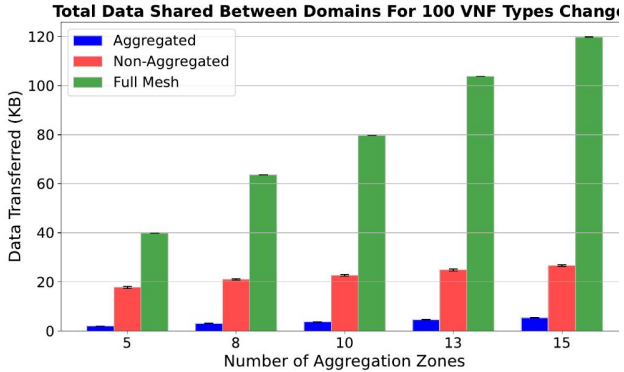


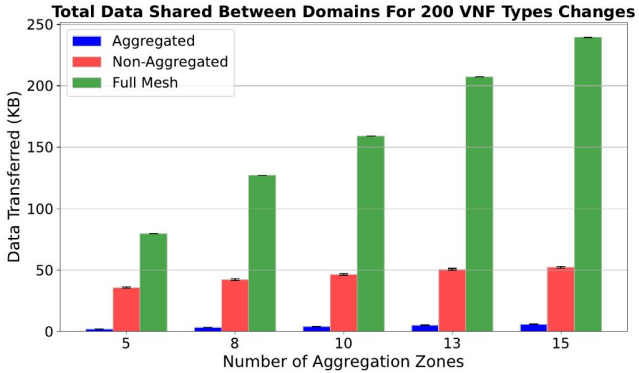


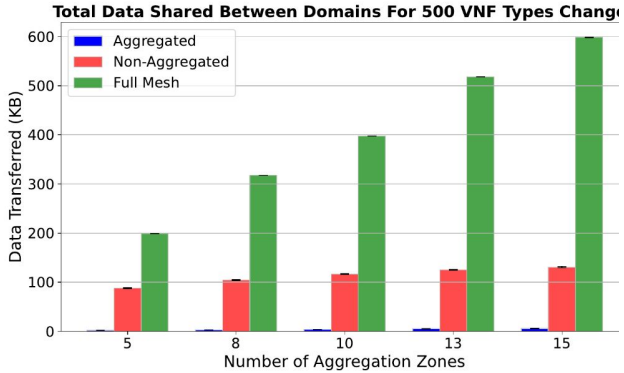
Meta Data Aggregation

Assess how metadata aggregation influences network efficiency.



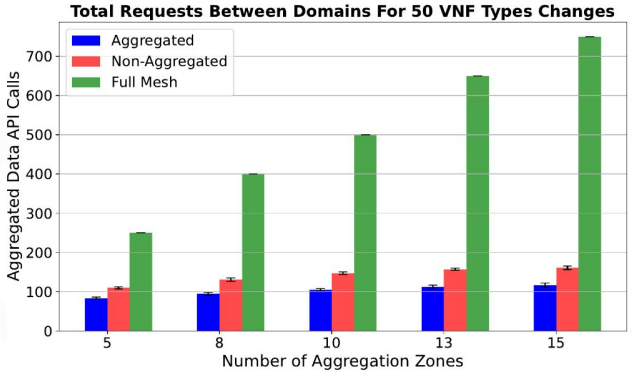


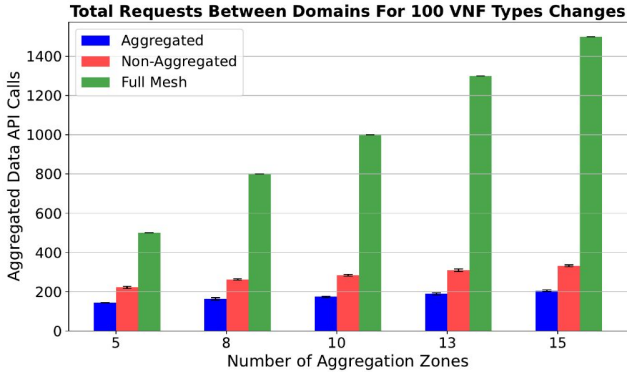


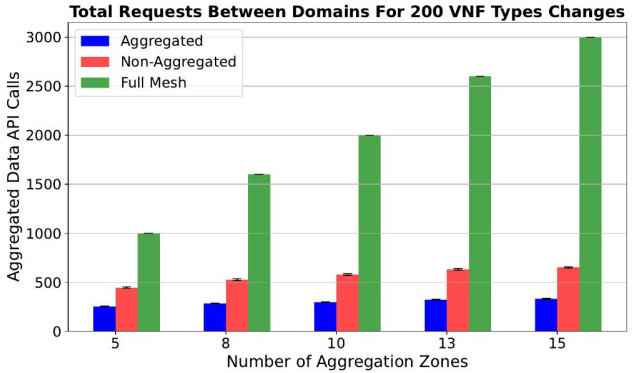


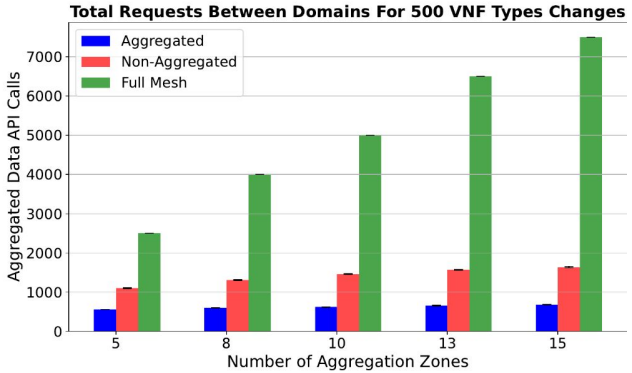
Total Requests API Calls Between Domains

Evaluate how the number of available VNF types changes influences resource consumption in aggregation zones.



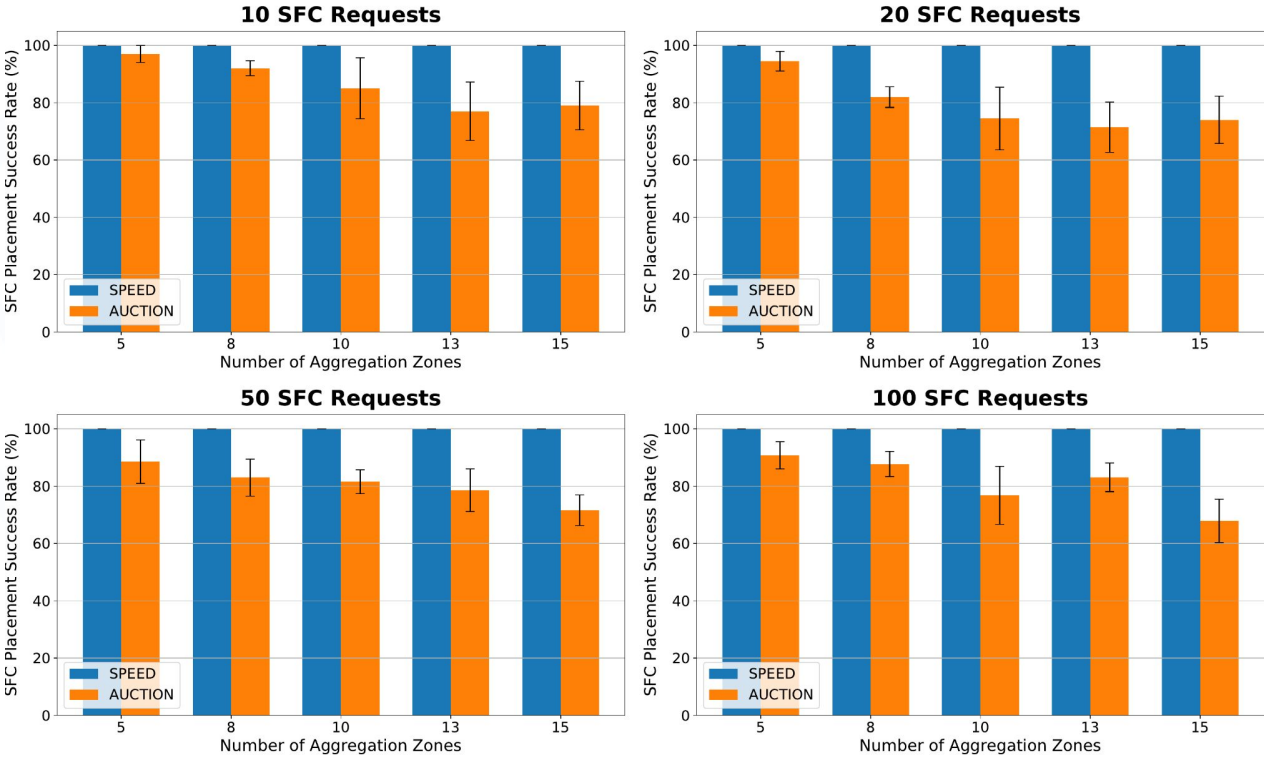






Comparison SPEED approach with an Auction-based strategy

Evaluate the SFC Placement success rate of the proposed solution relative to the auction approach.
(Avasalcai et al., 2019)
(Macedo et al., 2022)



Conclusion

- Main Contributions
- Research Questions
- Current Scientific Production

Main Contributions

- A **novel approach**, named **SPEED**, for solving the SFC Placement Problem in multi-domain environments, adopting a **distributed approach**
- A **novel architecture** that enables the execution of **SFCs across multiple domains**
- A **new system model** that maps the **SFC Placement Problem as a singleton congestion games**

Main Contributions

- **A novel strategy for structuring meta data** that enables the sharing of VNF metadata information across domains in **distributed environments**
- An **original method** for solving the **SFC Segmentation Problem** that can be used in multiple distributed SFC Placement algorithms

Answering the Research Questions

- **Q1: How can Game Theory be used to solve the Service Function Chain Placement Problem (SFCPP) in a multi-domain Edge-Cloud continuum?**
  - We provided a description of the proposed solution
  - We formalized the modeling of the SFC Placement Problem as a Singleton Congestion Game
  - We detailed the algorithms for identifying the manager zone and the processes by which the games are executed

Answering the Research Questions

- **Q2: How does the proposed approach contribute to reducing the monetary cost of executing SFCs in a multi-domain Edge-Cloud continuum?**
  - We conducted multiple experiments to evaluate our proposed approach
    - Simulations demonstrated that our approach was able to find suitable placement plans. However, the execution cost was not the lowest possible when compared to the auction-based method

Answering the Research Questions

- **Q3: How does the proposed approach contribute to increasing the SFC placement success rate in a multi-domain Edge-Cloud continuum?**
  - We ran experiments showing that our approach was 20% less effective than the best solution found via ILP, but 15% more effective than other

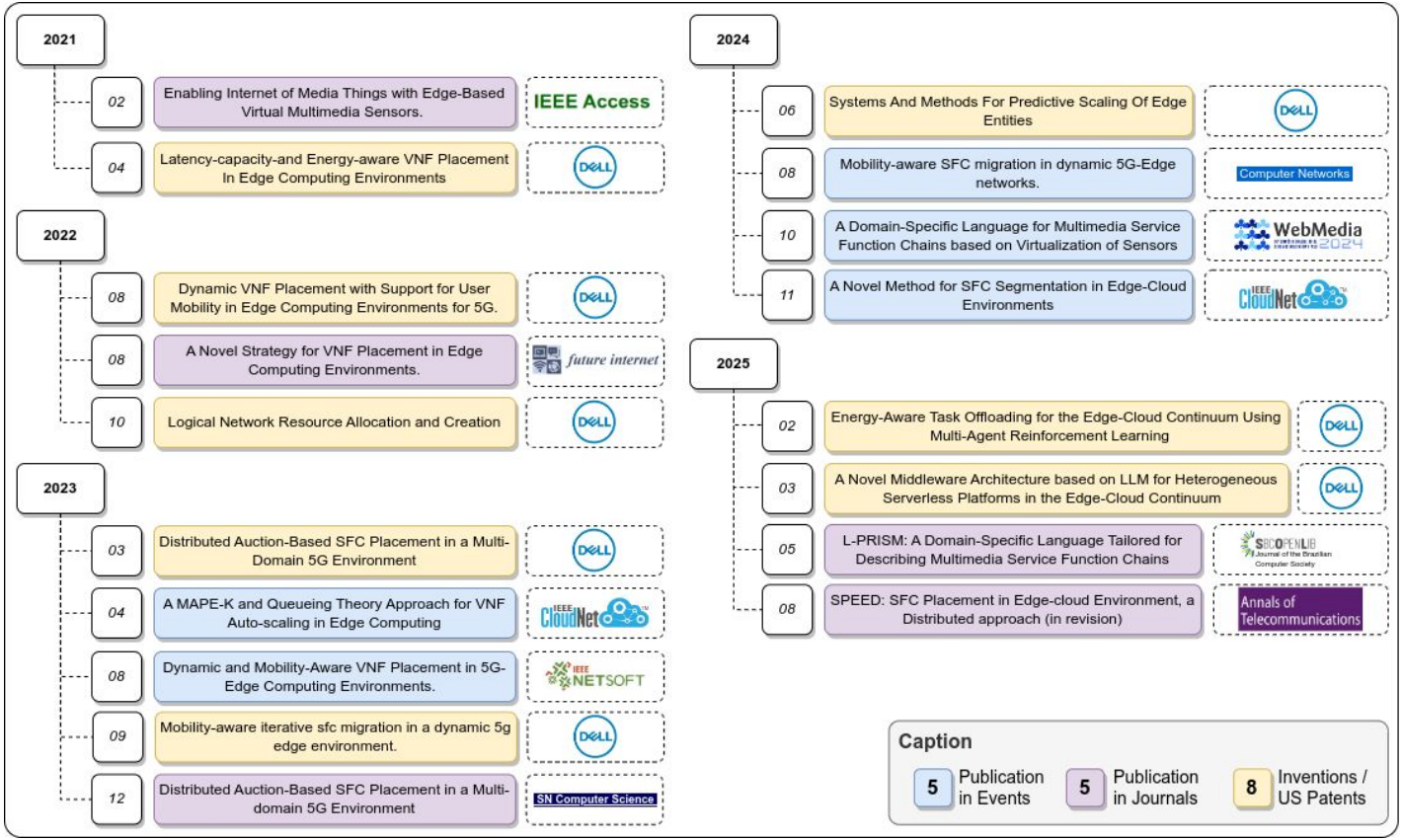
Limitations

- **Comparison** with other approaches was **limited by code availability** and compatibility, reinforcing the need for a common evaluation platform for SFC Placement solutions
- The use of a **single VNF type** may have affected the results

Future Work

- **VNF Migration Use Case**
  - SCGs can guide the selection of the most suitable compute zone for relocating a VNF to maintain service quality
- **Flexible Topologies**
  - Moving from hierarchical data sharing toward flexible topologies, with metadata sharing modeled by probabilistic methods (e.g., Markov processes)

Research Publications and Developed Projects



SPEED

SFC Placement in Edge-Cloud Continuum: a Distributed Approach

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