ΠΑΝΕΠΙΣΤΗΜΙΟ ΠΕΙΡΑΙΩΣ

UNIVERSITY OF PIRAEUS

THESIS:

Algorithms for Network Functions Coordination and Placement in Network Function Virtualization (NFV) simulated environment

Author: Christos Kopsacheilis

Supervising Committee:
Kostas Tsagkaris, Athanasios Kanatas,
Angelos Rouskas

Athens 2021

Abstract

Network Function Virtualization (NFV) is the current concept and the network architecture used from the majority of the providers and operators that get rid of network functions (such as firewalls, DNS, NATs, load balancers, intrusion detection devices, WAN accelerators, etc.) from dedicated hardware devices. This decoupling enables hosting of network services, known as Virtualized Network Functions (VNFs), on commodity hardware (for example switches or servers) and thus facilitates and speeds service deployment and management by providers, improves flexibility, leads to more efficient and scalable resource allocation and usage, and reduces in general the costs as the virtualized services can run on less expensive, generic servers instead of proprietary hardware. This concept is a new chapter in the evolution of networking, as it introduced high expectations for enhanced economical network services, as well as major technical challenges that are currently been researched.

This thesis addresses three baseline algorithms(Random Schedule, Shortest Path, and Load Balance) along with the results achieved by applying them on the problem of Coordination and Placement in a Network Function Virtualization (NFV) simulated environment. That is the problem for coordination of service mesh consisting of multiple microservices. This topic is always under constant analysis and research from many operators , as the coordination of the services is a complicated a problem and proposals for better solutions are currently analyzed from many Research and University Departments.

To the new generation

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1 Introduction

Today, ITC (Information Technology companies) and universities research and use more and more about the Network Function Virtualization (NFV) concept. In essence, Communications Service Providers (CSPs) and Internet Service Providers (ISPs) are dealing with competition from Over the top (OTT) media services and web services, experiencing declining average income per user and have the pressure to innovate quickly to respond to new technologies such as IoT (Internet of Things), 5G(preparing 6G as well), and cloud edge computing.

Proprietary single-function boxes are chained together in order for Traditional network services to be built. The design of these services is not standard, the thechnology used is not cheap, require lengthy and thorough prior analysis before deployed and most of the times cannot be shared with any other service. Once deployed, the operations and management of these services are largely non-automated, with each box presenting its own management interface. This technique of creating network services is very expensive, and offers no practical way of creating dynamic services.

NFV is the key-technology currently used by most of the operators, that can assist in solving these business challenges. Once virtualized, the Virtual Network Functions (VNFs) can be hosted on commodity hardware or a server. Virtualization does not stop at replacing physical boxes with virtual machines, but can go further by using microservices, containers, and cloud native techniques. Managing the Lifecycle of these services (such as initial deployment, configuration changes, upgrades, scale-out, scale-in, self-healing, etc.), can also be automated. These VNFs can also be chained and managed in a dynamic and automated fashion. All these advances enable the creation and management of flexible network services.

1.1 Thesis organization

This thesis is organized into 4 core chapters (introduction not included). Besides the present chapter introducing the context , objectives and contributions of the thesis, the manuscript is organized as follows:

- **Chapter 2** provides the background information related to this thesis. It presents an overview of what NFV is. The chapter also gives an overview of the state of the art of the in NFV and reviews the positive impact that this concept brings.
- **Chapter 3** provides the main topic of the thesis , which are the algorithms proposed for the VNF - Service function (SF) service coordination and flow scheduling problem along with the results by using the proposed algorithms(Concept, Experimentation platform and Results).
- **Chapter 4** provided some conclusions regarding the chapter 3 analysis.
- **Chapter 5** provides some future directions, regarding the thesis Problem and what can be further researched.

2 State of the Art

2.1 Introduction

Software-Defined Networking (SDN) and Network Function Virtualization (NFV) are enabling network programming and the automated provisioning of virtual networking services. Combining these paradigms , we can overcome the limitations of traditional clouds and networks by enhancing their dynamic networking capabilities. Since these paradigms have motivated this thesis and our investigations, this chapter on the state of the art will provide an overview of NFV architecture, resource allocation challenges and reflect the convergence trend between cloud computing, software networks, and the virtualization of Service functions.

2.2 Network Function Virtualization (NFV)

2.2.1 Network Services before NVF

Communication Service Providers (CSPs) go beyond simply providing network connectivity for their enterprise customers. They also offer additional services and network functions like Network address translation (NAT), Firewall, Encryption, Domain Name Service (DNS), Caching, etc. Traditionally, these network functions were deployed using proprietary hardware at the customer premises. This approach provides additional revenue but deploying multiple proprietary devices is costly and makes upgrades difficult (i.e., every time a new network function is added to a service, a truck roll is required to install the dedicated new hardware device). Consequently, service providers began exploring ways to reduce cost and accelerate deployments through Network Function Virtualization (NFV).

2.2.2 What is NVF?

Network Function Virtualization (NFV) [1], [2], [3] is an innovative way to design, deploy, and manage networking services by decoupling functions (such as firewalls, DPIs, load balancers,Service functions, etc.) from dedicated hardware and moving them to virtual servers. Several use cases of NFV are discussed in [4]. Note that manageability, reliability, stability, and security are considered in [4] as the key performance parameters in both physical and in software based virtualized networks.

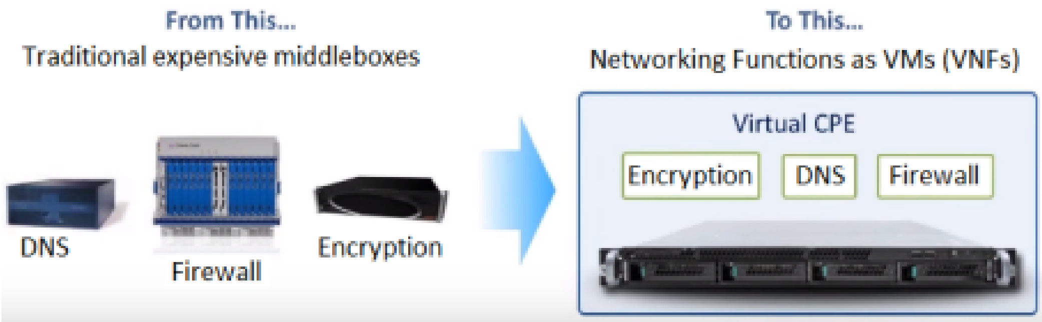

Figure 1: Network Function Virtualization

- **Hardware Flexibility:** Due to the fact that NFV regularly uses Commercial-Off-The-Shelf (COTS) hardware, network administrators have the freedom to select and build the hardware the most effective way to suit their needs and requirements.
- **Scalability and Elasticity:** New services and capacity-hungry applications keep network operators (especially cloud providers), on their toes to keep up with the fast increasing demands of consumers. Scaling the network architecture with virtual machines is faster and easier, and it does not require purchasing additional hardware.
- **Reduced Power Consumption and Complexity:** Efficiency in space, power, and cooling. Communications service providers (CSPs) may be physically restricted space, electricity and cooling capacity in a data center, so they will choose equipment carefully to consume these finite and/ or expensive items effectively resources. NFV provides better energy efficiency resulting from consolidation resources.
- **Faster Life Cycle:** New network services can now be deployed more quickly, in an on-demand and on-need basis, providing benefits for end users as well as the network providers.
- **Increased Revenue:** The combination of introducing new services faster and existing servers in a more dynamic way can jointly result in increased revenue.
- **Reduced Capital Expenditures:** The use of industry-standard services, increased hardware utilization and adoption of open source software results in reduced capital expenditures. Because NFV runs on virtual machines instead of physical machines, fewer appliances are necessary and operational costs are lower.
- **Reduced Operational Expenditures:** Automation and hardware standardization can substantially slash operational expenditures.

- **Improved Customers' Satisfaction:** The combination of service agility and self service can result in greater customer satisfaction.

2.2.3 What is SDN?

Software-Defined Networking (SDN) is a network architecture approach that allows the network to be intelligently and centrally controlled or programmed using software applications. This helps operators manage the entire network consistently and holistically, regardless of the underlying network technology.

Businesses, carriers and service providers are surrounded by a number of competing forces. The monumental rise of multimedia content, the explosion of cloud computing, the impact of rising mobile usage and ongoing business pressures to reduce costs, while revenues remain stable, all converge to destroy traditional business models.

SDN enables the programming of network behavior in a centrally controlled manner through software applications using open APIs. By opening up traditionally closed network platforms and implementing a common SDN control layer, operators can manage the entire network and its devices consistently, regardless of the complexity of the underlying network technology.

SDN represents a substantial step forward from traditional networking, in that it enables the following:

- **Increased control with greater speed and flexibility:** Instead of manually programming multiple hardware devices for specific vendors, developers can control the flow of traffic over a network simply by programming an open standard software-based controller. Network administrators also have more flexibility in choosing networking equipment, as they can choose a single protocol for communicating with any number of hardware devices through a central controller.
- **Customizable network infrastructure:** With a software-defined network, administrators can configure network services and allocate virtual resources to change the network infrastructure in real time through a central location. This allows network administrators to optimize network data flow and prioritize applications that require more availability.
- **Robust security:** A software-defined network provides visibility across the network, providing a more holistic picture of security threats. With the pro-

liferation of smart devices connected to the Internet, SDN offers clear advantages over traditional networking. Operators can create separate zones for devices that require different levels of security, or immediately quarantine devices so that they can not infect the rest of the network.

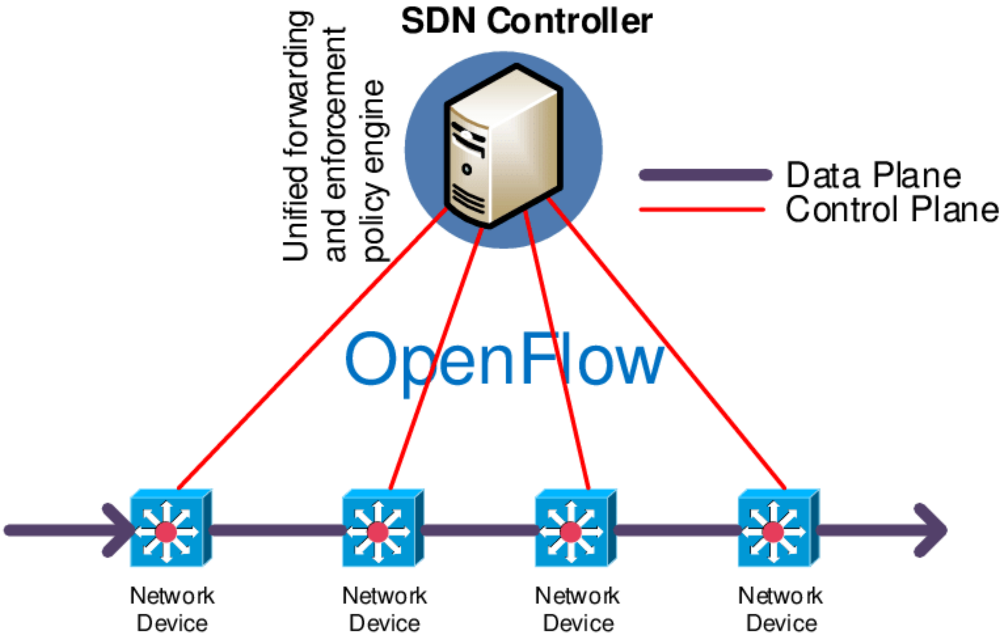

Figure 2: A schematic overview of SDN implemented with OpenFlow

The main difference between SDN and traditional networking is infrastructure: SDN is software-based, while traditional networking is hardware-based. Because the control level is software-based, SDN is much more flexible than traditional networking. It allows administrators to control the network, change configuration settings, power supplies, and increase network capacity, all from one central user interface, without the need for more hardware.

There are also security differences between SDN and traditional network. Thanks to greater visibility and the ability to define safe routes, SDN offers better security in many ways. However, because software-defined networks use a central controller, controller security is critical to maintaining a secure network.

2.2.4 NFV Architecture

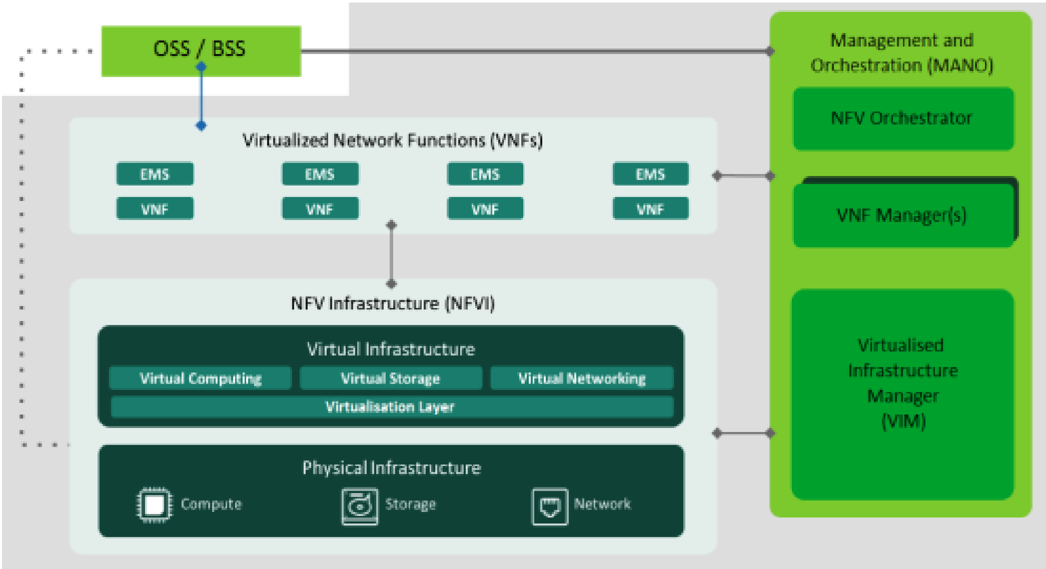

Figure 3: ETSI NFV reference architecture

The main components of the NFV architectural framework are:

1. NFV Infrastructure (NFVI): is a type of cloud data center that contains the whole hardware and software components that create the NFV environment in which NFV services are developed, managed and implemented. NFVI includes:

- **Physical Hardware:** This includes computer hardware (such as servers, RAM), storage (such as disk storage, Network Attached Storage (NAS)) and network hardware (such as switches and routers).
- **Virtualisation Layer:** removes hardware resources and decouples VNF software from the underlying hardware, thus ensuring independent hardware life cycle for VNFs. We can use many open source and proprietary options for the virtualization layer (such as KVM, QEMU, VMware and Openstack or any other custom environment).
- **Virtual Infrastructure:** this includes virtual compute (virtual machines or containers), virtual storage, and virtual networks (overlay networks).

2. **Virtualised Network Functions (VNFs):** run on top of NFVI and represent virtual instances of different network functions. This framework is essential for managing network and infrastructure functionality.

3. **NFV Management and Orchestration (MANO):** NFV MANO does not work individually. It interacts with operational/business support systems (OSS/BSS) of the operator for the management of operational and business aspects network. MANO includes:

- **Virtualized Infrastructure Manager (VIM):** or cloud management software, e.g. OpenStack or Kubernetes. It is responsible for the control and management of the computing, storage and network resources, as well as their virtualization.
- **VNF Manager(s):** it is responsible for VNF life cycle management, including VNF instantiation/ onboarding, update, query, scaling in/out, and termination.
- **NFV Orchestrator:** it is in charge of the orchestration and management of NFV infrastructure and software resources, and realizing network services on NFVI. It utilizes resource allocation and placement algorithms to ensure optimal usage of both physical and software resources.

2.3 Integration of NFV with other technologies

In recent years, the integration of NFV with other technologies, such as SDN, Cloud computing, and 5G [5] has attracted significant attention from both academic / university research community and industry. Integrating NFV with SDN and Cloud Computing is beneficial because of the complementary characteristics and discreet approaches followed by each technology to provide solutions in current and future networks [6], [7]. For instance, NFV provides function abstraction (i.e., virtualization of network functions) supported by ETSI [8], SDN provides network abstraction supported by Open Networking Foundation (ONF) [9], and Cloud computing provides computation abstraction (i.e., a shared pool of configurable computing resources (e.g., networks,, storage, applications, and services)) supported by the Distributed Management Task Force (DMTF) [10]. Abstraction is one of the key features of the cloud computer that allows the removal of the physical application to hide the background (technical) details from users and developers. To summarize the relationships between NFV, SDN, and Cloud computing, we use Figure 3.

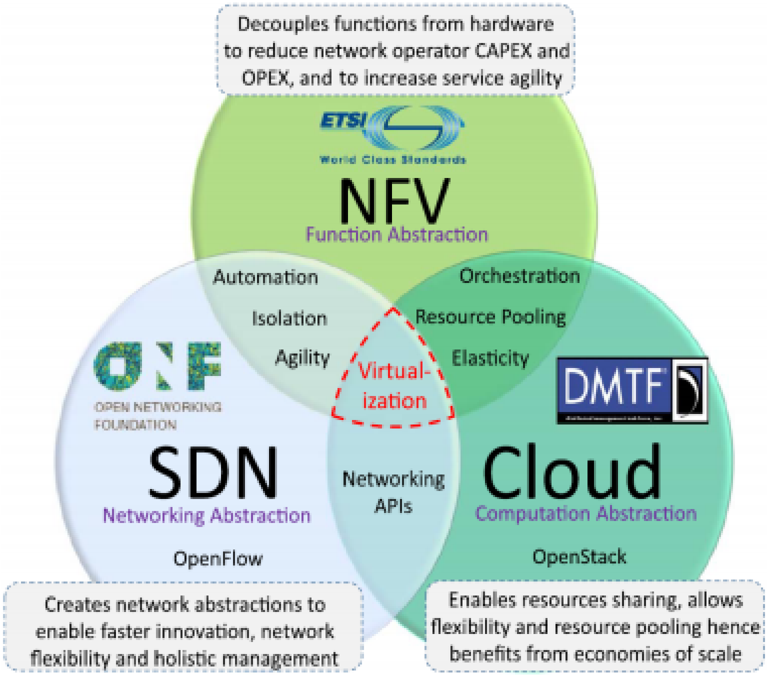

Figure 4: ETSI NFV reference architecture

SDN, NFV and Cloud computing technologies are complementary but they are independent and can be developed alone or together. Combining these technologies together in a network architecture is more desirable [11]. In fact, the benefits concentrated for each of them are similar: agility, cost reduction, dynamism, automation, escalation etc.

2.4 The scope of the analysis and targets of this studying

In this project, we formulate the VNFs service mesh co-ordination and placement problem and then suggest different algorithms for solution. In particular, we propose three algorithms that perform the co-ordination of service mesh of VNFs:

1. A Random Schedule algorithm which is a dummy/ random decison algorithm.

2. A Load Balance algorithm which always returns equal distribution for all nodes having capacities and SFs. Places all SFs on all nodes having some capacity.

3. A Shortest Path algorithm.

Finally, in order to evaluate the above algorithms results we create an NFV simulated environment with a real network topology (Abilene topology).

3 Virtual Service and flow coordination

3.1 Concept - Problem statement

There is a growing demand for services consisting of multiple interconnected elements, e.g. micro-services in one service Grid or Chained Virtual Network Functions (VNFs) in Network Function Virtualization (NFV) [12]. These services can scale flexibly by instantiating service components according to current demand. Such instances can be executed independently on any compute node in the network and process incoming flows requesting service. Service provisioning and coordination in networks with geographically and topologically distributed compute nodes is a continuing challenge. In edge and fog computing, this challenge is exacerbated by limited computational capabilities as well as connection delay between nodes. Furthermore, service demand in terms of incoming flows is also distributed across the network and varies over time. Services can consist of multiple interconnected components, which process incoming flows.

The goal of service coordination and placement is to ensure that these flows are processed successfully by traversing instances of all required service components. In addition, flows must complete with a short end-to-end delay to ensure good quality of service (QoS). For this purpose, the requested services need to be scaled and their instances placed in the network, i.e., we have to decide how many service components to instantiate where. Furthermore, incoming flows need to be routed from their ingress nodes through these deployed instances and finally to their egress nodes. In doing so, node and link capacities need to be respected and link delays should be considered.

To address the issue three algorithms proposed were evaluated, a simulation environment was deployed proposed as suggested at [12] . Algorithms used: Random Schedule,Load Balance algorithm and Shortest Path algorithm (more details of these algorithms will be discussed in the next section).

Real graph network topology was used as input in the simulated environment with ”fake” flow traffic produced from the author, in order to test the algorithms in this environment and view what co-ordination we achieved using these algorithms and then compare them.

3.1.1 Problem Formulation

We address the problem of coordinating services online over discrete time steps $t \in \mathbb{T}$. The problem can be formalized as follows:

A. Problem Inputs

We consider a substrate network $G = (V, L)$ of distributed nodes connected by non-directed links. Each node $u \in \mathbb{G}$ has a compute capacity $cap_u \in \mathbb{R}$ (e.g CPU). Each $link = (u, u') \in \mathbb{L}$ connects two nodes u and u' bidirectional with certaind delay $d_t \in \mathbb{R}$ and a maximum data rate $cap_t \in \mathbb{R}$ that is shared between both directions. We will also need to declare the Service Functions (SF) in order to apply the algorithms with deterministic processing delays. Finally we configure the NFV simulator, in order to have the complete solution deploeyd for testing - research.
In mathematical Formulation our goal is the below:

$$\max o_f = \frac{|F_{\text{succ}}|}{|F_{\text{succ}}| + |F_{\text{drop}}|} \tag{1}$$

$$\min o_d = \frac{1}{|F_{\text{succ}}|} \sum_{f \in F_{\text{succ}}} \sum_{c \in C_{s_f}} d_c + \sum_{\substack{(v,v')=l \in L, \\ c \in C_{s_f}, t \in T}} \mathbb{1}_{\{y_{f,c,v}(t)=v'\}} d_l \tag{2}$$

Figure 5: Mathematical formulation

Maximizing objective of means to process as many flows successfully (F_s) as possible, avoiding dropped flows (F_d), thus maximizing the percentage of successful flows (eq. 1).

At the same time, the goal is to minimize the objective delay function, which is the average end-to-end delay in all successful flows (eq. 2). The end-to-end delay of a flow f consists of two parts. First, the sum of processing delays d_c of components c whose instance f traversed. And second, the sum of link delays d_l that f experienced during routing. In eq. 2, 1 $y_f, c, v(t) = v_0$ is an indicator variable that is 1 if f traversed link $l = (v, v_0)$ and 0 otherwise. Note that the two objectives of and od may be conflicting. For example, distributing flows over more nodes and links to balance the load helps with processing more flows successfully (improves of) but also leads to longer paths and higher end-to-end delays (degrades O_d). In our algorithms, we approach this trade off by optimizing of and O_d in lexicographical order, i.e., prioritizing of but still trying to optimize O_d as far as possible

3.1.2 Algorithms proposed

In this section we will have a high level look on the algorithms that we are going to use.

Random Schedule:

- Places all VNFs on all nodes of the networks
- Creates random schedules for each source node, each SFC, each SF , each destination node
- All the schedules for an SF sum-up to 1

Load Balance algorithm:

- Always returns equal distribution for all nodes having capacities and SFs. Places all SFs on all nodes having some capacity.

Shortest path algorithm:

Based on network topology, SFC, and ingress nodes, calculates for each ingress node:

- Puts 1st VNF on ingress, 2nd VNF on closest neighbor, 3rd VNF again on closest neighbor of 2nd VNF and so on.
- Stores placement of VNFs and avoids placing 2 VNFs on the same node as much as possible. If all nodes are full, continue to place a 2nd VNF on all nodes, but avoid placing 3 VNFs and so on.
- Avoids nodes with no capacity (but ignores current utilization).

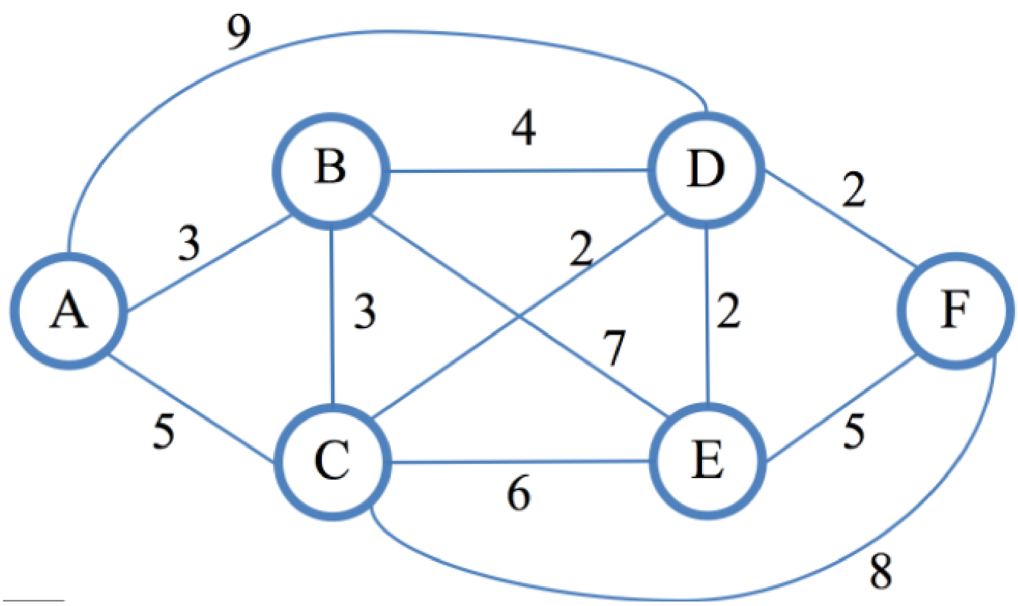

Figure 6: Shortest path Algorithm

3.2 Experimentation Platform

We evaluate our three proposed algorithms(RS, LB, SP), using extensive simulations on the real-world Abilene network topology [13] with 11 nodes and 14 links. We consider the Abilene network to be a representative example of a small scale networks in practice. The simulator is based on SimPy and is tested with Python 3.8. We set randomly pick heterogeneous node capacities $capv \in (0, 7, 14)$.

Figure 7: Abilene topology graph

SimPy: SimPy is a process-based discrete-event simulation framework based on standard Python.

Procedures in SimPy are defined by the functions of the Python generator and can, for example, be used to model active components, such as clients, vehicles, or agents. SimPy also provides various types of shared resources for modeling limited capacity bottlenecks (such as servers, cash registers, and tunnels).

Simulations can be performed ”as fast as possible”, in real time (wall clock time) or by manually stepping through the events.

This discrete-event flow-based simulator is a fast testbed for VNF coordination algorithms. It is designed to simulate small to medium-sized networks with relatively near-reality accuracy. It can interact with coordination algorithms through an interface that can be customized by the algorithm developers.

Furthermore, we consider the SFCs (a, b, c) all with mean processing delay $processorDelayMean = 5$ and standard deviation $stdev = 0$

Also, they incur a per-flow processing delay that is normally distributed with N (5 ms, 0 ms), where values are cut off at 0 ms to prevent negative delays. Flows arriving at the network's ingress nodes request one of the three services chosen uniformly at random. For each ingress, flow inter-arrival times mean is set to 12 , flow duration $dfMmean = 1$, and flow data rate standard deviation is set to 0. The duration per experiment is $|T| = 1000$ time steps.

3.2.1 Simulation

The simulations are based on a realistic network topology were run in a 1.60 GHz Quad Core machine with 16 GBytes of available RAM.

In order to run the test Ubuntu Operating system was install with WSL2 (Ubuntu running on Windows Kernel), using python 3.8.

The file structure of the simulator is as follows[14]: - docs (Folder): Contains the documentation files of the project. - params (Folder): Contains sample parameter files (network file and VNF file) for testing purposes. - src (Folder): Contains the source code for the simulator and the interface. - coordsim (Folder): contains the source code of the simulator - metrics (Folder): contains the metrics module. - network (Folder): contains the network module. - reader (Folder): contains the params file reader module. - simulation (Folder): main simulator module. - main (Python): main executable for running the simulator from CLI - siminterface (Folder): contains the interface source code - tests (Folder): contains the unit tests for the simulator.

The simulator works as follows: The user (coordination algorithm or cli) provides two main inputs for the simulator: - Network file: GraphML file using the Zoo format. This file contains network nodes and edges. - VNF file: YAML file containing the list The SFCs and the list of SFs under each SFC in order. The file may also include a defined placement that can be used as the default placement. SFs must include one average processing delay and standard deviation values so that processing is delayed is calculated for each flow passing through this SF.

Once the parameters are provided, the flow of data through the simulator is as follows:

- The input network and VNF files are parsed to create a NetworkX object that contains the list of nodes and edges and the shortest network paths (using Floyd-Warshall). The parsing also produces dictionaries containing the list of SFCs and the list of SFs and their respective values. Additionally, the list of ingress nodes (nodes at which flows arrive) are also calculated from the GraphML file. These parameters are then passed to a SimulatorParams object, which has all the parameters of the simulator, the simulator is then started using the FlowSimulator object's start() $function$.

- At each ingress node, the $function$ generateFlow() is called as a SimPy process, this $function$ creates Flow objects with exponentially distributed random inter arrival times. Flow data rate and size are generated using normally distributed random variables. All of the inter arrival time, data rate, and flow size parameters are user configurable. The flow is also assigned a random SFC chosen from the list of available SFC given in the VNF file.

- Once the flow is generated, initFlow() is called as a SimPy process which initializes the handling of the flow within the simulator. The $function$ then calls passFlow(), which then handles the scheduling of the flow according to the defined load balancing rules (flow schedule). Once the next node has been determined, the forwarding of the flow is simulated by halting the flow for the path delay duration using the forwardFlow() $function$. Once that is done, the processing of the flow is simulated by calling processFlow() as a SimPy process. If the requested SF was not found at the next node, the flow is then dropped.

- In processFlow(), the processing delay for that particular SF is generated using given mean and standard deviation values using a normal distribution. The simulator checks the node's remaining processing capacity to check if the node can handle the data rate requested by the SF, if there is not enough capacity, then the flow is dropped. For the duration that the flow is being processed by the SF, the flow's data rate is deducted from the node's capacity, and returned after the flow finished processing completely.

- Once the flow was processed completely at each SF, departFlow() is called to register the flow's departure from the network. If the flow still has other SFs to be processed at in the network, processFlow() calls passFlow() again in a mutually recursive manner. This allows the flow to stay in the SF for processing, while the parts of the flow that were processed already to be sent to the next SF.

Input Parameters: The available input parameters that can be configured by the user are: - d: The duration of the simulation (simulates milliseconds). - s: The seed to use for the random number generator. - n: The GraphML network file that specifies the nodes and edges of the network. - sf: VNF file which contains the SFCs and their corresponding SFs and their properties. - iam: Inter arrival mean of the flows' arrival at ingress nodes. - fdm: The mean value for the generation of data rate values for each flow. - fds: The standard deviation value for the generation of data rate values for each flow. - fss: The shape of the Pareto distribution for the generation of the flow size values.

The simulation environment has the following features:

- ▶ Simulate any given network topology with arbitrary node and link capabilities and link delays
- ▶ Simulate any given network service consisting of linearly chained SFs/ VNFs
- ▶ VNFs can define arbitrary resource consumption as a function of their load using Python modules. Also, the VNF delay can be determined separately and can be normally distributed.
- ▶ Simulate network traffic in the form of flow arrivals at various ingress nodes with different arrival rate, flow length, volume, etc. according to the stochastic distributions
- ▶ Simple interface to run algorithms for scaling, placement, and scheduling/load balancing of these incoming flows across the nodes in the network.
- ▶ Collection of measurements such as successful/dropped flows, end-to-end delay, resource consumption, etc over time. Easily extensible.
- ▶ Discrete event simulation for evaluation of coordination over time with SimPy
- ▶ Graceful adjustment of placements: When VNFs are removed from a placement by an algorithm.

In our case we used the following as input:

In figure 7 we see the graphml file of Abilene graph topology that was used for this thesis as viewed in Gephi application.

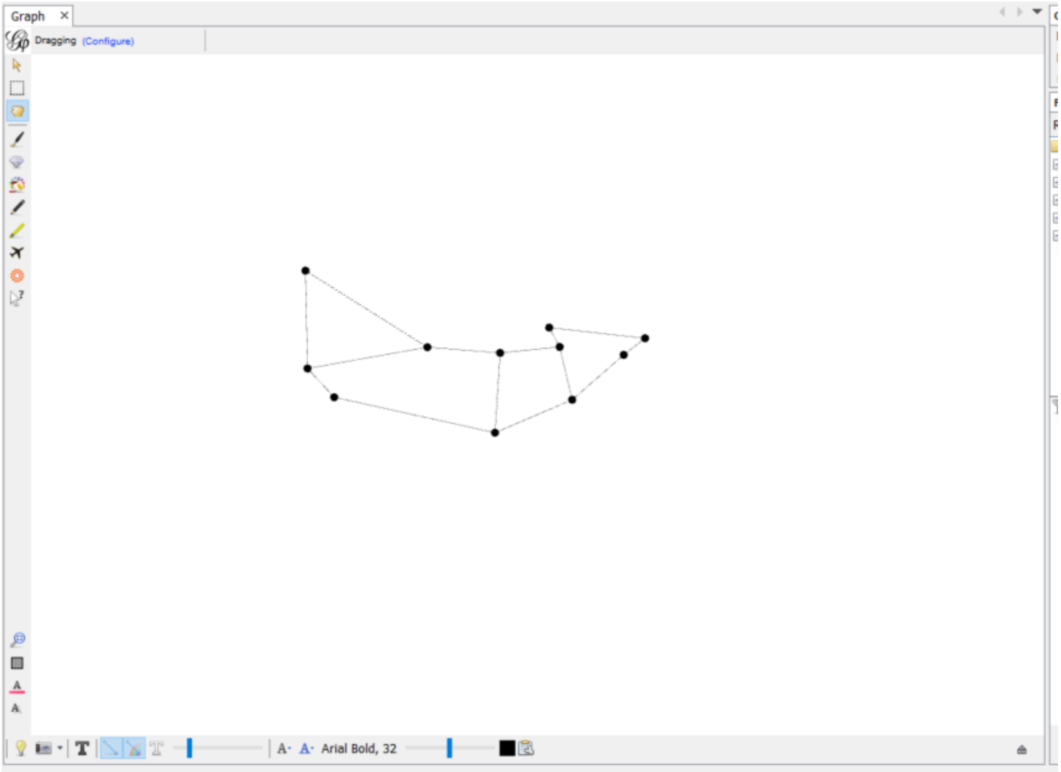

Figure 8: Abilene graphml as viewed in Gephi

In figure 8,9 we see the graphml data of Abilene graph topology that was used for this thesis as viewed as well in Gephi application.

Id	Label	Interval	NodeCap	NodeType	Longitude	id	Country	Latitude	Internal
0	New York		0	Ingress	-74.00597	0	United States	40.71427	1
1	Chicago		7	Ingress	-87.65005	1	United States	41.85003	1
2	Washington DC		0	Ingress	-77.03637	2	United States	38.89511	1
3	Seattle		14	Ingress	-122.33207	3	United States	47.60621	1
4	Sunnyvale		7	Ingress	-122.03635	4	United States	37.36883	1
5	Los Angeles		14	Normal	-118.24368	5	United States	34.05223	1
6	Denver		0	Normal	-104.9847	6	United States	39.73915	1
7	Kansas City		0	Normal	-94.62746	7	United States	39.11417	1
8	Houston		14	Normal	-95.36327	8	United States	29.76328	1
9	Atlanta		7	Normal	-84.38798	9	United States	33.749	1
10	Indianapolis		7	Normal	-86.15804	10	United States	39.76838	1

Figure 9: Abilene network topology data(1)

Graph | Data Table

Nodes Edges | Configuration | Add node | Add edge | Search/Replace | Import Spreadsheet | Export table | More actions | Filter: | Source

Source	Target	Type	Id	Label	Interval	Weight	LinkFwdCap	key	LinkNote	LinkLabel	LinkType
0	1	Undirected	0			1.0	1000	0	c	OC-192c	OC-192
0	2	Undirected	1			1.0	1000	0	c	OC-192c	OC-192
1	10	Undirected	2			1.0	1000	0	c	OC-192c	OC-192
2	9	Undirected	3			1.0	1000	0	c	OC-192c	OC-192
3	4	Undirected	4			1.0	1000	0	c	OC-192c	OC-192
3	6	Undirected	5			1.0	1000	0	c	OC-192c	OC-192
4	5	Undirected	6			1.0	1000	0	c	OC-192c	OC-192
4	6	Undirected	7			1.0	1000	0	c	OC-192c	OC-192
5	8	Undirected	8			1.0	1000	0	c	OC-192c	OC-192
6	7	Undirected	9			1.0	1000	0	c	OC-192c	OC-192
7	8	Undirected	10			1.0	1000	0	c	OC-192c	OC-192
7	10	Undirected	11			1.0	1000	0	c	OC-192c	OC-192
8	9	Undirected	12			1.0	1000	0	c	OC-192c	OC-192
9	10	Undirected	13			1.0	1000	0	c	OC-192c	OC-192

Figure 10: Abilene network topology data(2)

In figure 10 we see the yaml file of the simulator configuration that was used.

```yaml
# module for configuring the simulator
# configuration parameters are loaded and used both when using the simulator via the CLI and via the interface
# all parameters are required, defaults are in comments

inter_arrival_mean: 12.0          # default: 10.0
deterministic_arrival: False
flow_dr_mean: 1.0                 # default: 1.0
flow_dr_stdev: 0.0                # default: 0.0
flow_size_shape: 0.001              # default: 0.001
deterministic_size: True
run_duration: 100                  # default: 100
ttl_choices: [100]

# Optional: Trace file trace relative to the CWD.
# Until values start in the trace file, the defaults from this file are used
# trace_path: res/traces/scenario09.csv

# States (two state markov arrival)
# Optional param: states: True | False
use_states: True
init_state: state_1

states:
  state_1:
    inter_arr_mean: 12.0
    switch_p: 0.05
  state_2:
    inter_arr_mean: 8.0
    switch_p: 0.05
```

Figure 11: Simulation configuration (yaml file)

In figure 11 we see the yaml file of the SFC configuration that was used for the experiments.

```yaml
# simple chain of 3 SFs a->b->c with deterministic processing delays

# list of SFCs and involved SFs (order of SFs matters). names need to match dummy schedule and placement (dummy_data.py)
sfc_list:
  sfc_1:
    - a
    - b
    - c

# SF attributes (for now, processing delay)
sf_list:
  a:
    processing_delay_mean: 5.0
    processing_delay_stdev: 0.0
  b:
    processing_delay_mean: 5.0
    processing_delay_stdev: 0.0
  c:
    processing_delay_mean: 5.0
    processing_delay_stdev: 0.0

```

Figure 12: SFCs simulation configuration(abc.yaml)

3.2.2 Running the simulator

The simulator application is called rs for random schedule, lb for load balance and sp for shortest path. To run the simulator, the following command may be executed:

Usage

```
usage: rs [-h] [-i ITERATIONS] [-s SEED] -n NETWORK -sf
                   SERVICE_FUNCTIONS -c CONFIG

Dummy Coordinator

optional arguments:
  -h, --help            show this help message and exit
  -i ITERATIONS, --iterations ITERATIONS
  -s SEED, --seed SEED
  -n NETWORK, --network NETWORK
  -sf SERVICE_FUNCTIONS, --service_functions SERVICE_FUNCTIONS
  -c CONFIG, --config CONFIG
```

Figure 13: commands usage(example for rs)

In our case we ran the following commands:

```
rs -n "res/networks/abilene/abilene_5in_7x-cap.graphml" -sf "res/service_functions/abc.yaml" -c
"res/config/rand-mmp-arrival12-8_det-size001_dur100.yaml" -i 1000

lb -n "res/networks/abilene/abilene_5in_7x-cap.graphml" -sf "res/service_functions/abc.yaml" -c
"res/config/rand-mmp-arrival12-8_det-size001_dur100.yaml" -i 1000

sp -n "res/networks/abilene/abilene_5in_7x-cap.graphml" -sf "res/service_functions/abc.yaml" -c
"res/config/rand-mmp-arrival12-8_det-size001_dur100.yaml" -i 1000
```

Figure 14: commands used in CLI

And this is the output of the commands running in the terminal (mobaXterm application was used as terminal) in the simulated environment. (LOG level set to INFO in order no to use less memory, we can set it to Warning, Error, Info and Debug).

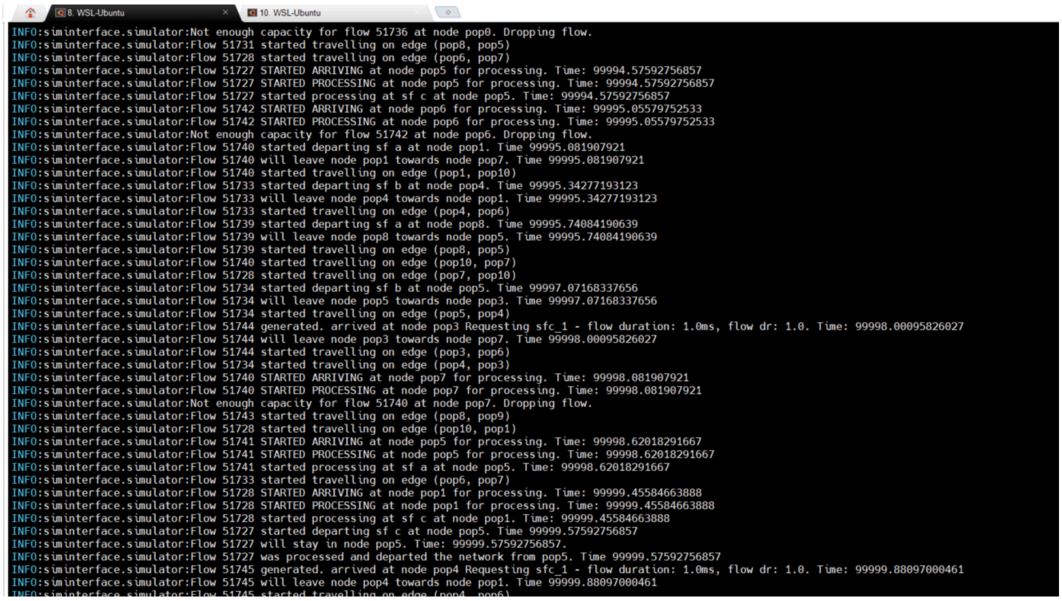

Figure 15: commands running

3.3 Results

The results and the inputs of the simulation are saved results under /usr/local/lib/python3.8/dist-packages/results/ in CSV format in order for the user to visualize and experiment with them. nodemetrics.csv has all the results concatenated in one file.

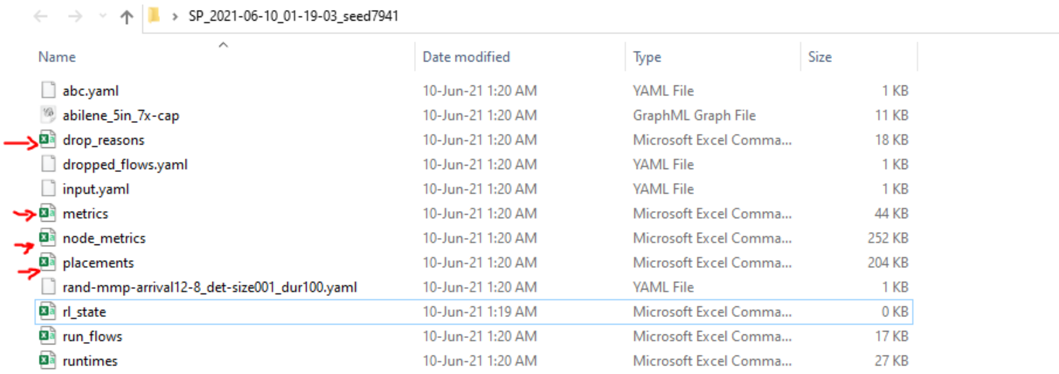

Figure 16: Results files

Next we will have a look of what was the output after running the simulator with the given algorithms.

3.3.1 Random Schedule Results

Results After running the Random schedule algorithm:

episode	time	total_flows	successful_flows	dropped_flows	in_network_flows	avg_end2end_delay
1	0	5	0	0	5	0
1	100	50	10	27	13	29.4
1	200	87	20	62	5	30.85
1	300	135	29	99	7	31.06896552
1	400	193	40	143	10	32.5
1	500	237	51	176	10	32.54901961
1	600	276	63	204	9	31.47619048
1	700	321	74	238	9	31.05405405
1	800	370	85	279	6	31.22352941
1	900	415	96	309	10	31.10416667
1	1000	457	105	346	6	31.37142857
1	1100	499	118	378	3	31.08474576
1	1200	541	131	404	6	31.10687023
1	1300	583	146	431	6	31.28767123
1	1400	623	156	455	12	31.15384615
1	1500	660	166	488	6	31.36746988
1	1600	694	171	515	8	31.35672515
1	1700	742	184	547	11	31.26630435
1	1800	782	196	581	5	31.43367347
1	1900	812	205	602	5	31.52195122
1	2000	856	214	634	8	31.57476636
1	2100	901	226	664	11	31.63716814
1	2200	951	242	702	7	31.85123967
1	2300	981	251	724	6	32.00796813
1	2400	1039	261	764	14	32.06130268
1	2500	1080	277	799	4	32.15884477
1	2600	1121	284	831	6	32.14788732
1	2700	1163	294	864	5	32.09863946
1	2800	1220	309	902	9	32.21359223
1	2900	1269	322	936	11	32.13043478
1	3000	1316	338	973	5	32.29881657
1	3100	1366	347	1014	5	32.26224784
1	3200	1411	356	1048	7	32.31741573
1	3300	1454	364	1083	7	32.36813187
1	3400	1512	377	1123	12	32.41909814
1	3500	1559	391	1157	11	32.48337596
1	3600	1602	409	1189	4	32.44498778
1	3700	1648	417	1220	11	32.441247
1	3800	1694	432	1255	7	32.49768519

metrics

Figure 17: Metrics after running rs script

episode	time	node	node_capacity	used_resources	ingress_traffic
1	0	pop0	0	0	0
1	0	pop1	7	0	0
1	0	pop2	0	0	0
1	0	pop3	14	0	0
1	0	pop4	7	0	0
1	0	pop5	14	0	0
1	0	pop6	0	0	0
1	0	pop7	0	0	0
1	0	pop8	14	0	0
1	0	pop9	7	0	0
1	0	pop10	7	0	0
1	100	pop0	0	0	5
1	100	pop1	7	3	10
1	100	pop2	0	0	10
1	100	pop3	14	3	11
1	100	pop4	7	1	14
1	100	pop5	14	4	0
1	100	pop6	0	0	0
1	100	pop7	0	0	0
1	100	pop8	14	4	0
1	100	pop9	7	2	0
1	100	pop10	7	2	0
1	200	pop0	0	0	7
1	200	pop1	7	2	5
1	200	pop2	0	0	9
1	200	pop3	14	2	9
1	200	pop4	7	3	7
1	200	pop5	14	3	0
1	200	pop6	0	0	0
1	200	pop7	0	0	0
1	200	pop8	14	3	0
1	200	pop9	7	2	0
1	200	pop10	7	2	0
1	300	pop0	0	0	13
1	300	pop1	7	2	6
1	300	pop2	0	0	7
1	300	pop3	14	3	9
1	300	pop4	7	3	13
1	300	pop5	14	3	0

node_metrics

Figure 18: Node Metrics after running rs script

episode	time	node	sf
1	0	pop0	a
1	0	pop0	b
1	0	pop0	c
1	0	pop1	a
1	0	pop1	b
1	0	pop1	c
1	0	pop2	a
1	0	pop2	b
1	0	pop2	c
1	0	pop3	a
1	0	pop3	b
1	0	pop3	c
1	0	pop4	a
1	0	pop4	b
1	0	pop4	c
1	0	pop5	a
1	0	pop5	b
1	0	pop5	c
1	0	pop6	a
1	0	pop6	b
1	0	pop6	c
1	0	pop7	a
1	0	pop7	b
1	0	pop7	c
1	0	pop8	a
1	0	pop8	b
1	0	pop8	c
1	0	pop9	a
1	0	pop9	b
1	0	pop9	c
1	0	pop10	a
1	0	pop10	b
1	0	pop10	c
1	100	pop0	a
1	100	pop0	b
1	100	pop0	c
1	100	pop1	b
1	100	pop1	a
1	100	pop1	c

placements

Ready

Figure 19: SF placements after running rs script

episode	time	successful	dropped_flo	total_flows
1	0	0	0	5
1	100	10	27	45
1	200	10	35	37
1	300	9	37	48
1	400	11	44	58
1	500	11	33	44
1	600	12	28	39
1	700	11	34	45
1	800	11	41	49
1	900	11	30	45
1	1000	9	37	42
1	1100	13	32	42
1	1200	13	26	42
1	1300	15	27	42
1	1400	10	24	40
1	1500	10	33	37
1	1600	5	27	34
1	1700	13	32	48
1	1800	12	34	40
1	1900	9	21	30
1	2000	9	32	44
1	2100	12	30	45
1	2200	16	38	50
1	2300	9	22	30
1	2400	10	40	58
1	2500	16	35	41
1	2600	7	32	41
1	2700	10	33	42
1	2800	15	38	57
1	2900	13	34	49
1	3000	16	37	47
1	3100	9	41	50
1	3200	9	34	45
1	3300	8	35	43
1	3400	13	40	58
1	3500	14	34	47
1	3600	18	32	43
1	3700	8	31	46
1	3800	15	35	46

run_flows

Figure 20: Run Flows after running rs script

3.3.2 Load Balance Results

Results After running the Load Balance algorithm:

episode	time	total_flows	successful_flows	dropped_flows	in_network_flows	avg_end2end_delay
1	0	5	0	0	5	0
1	100	47	33	0	14	32.75757576
1	200	97	80	0	17	33.4125
1	300	141	121	2	18	33.62809917
1	400	201	176	2	23	33.36931818
1	500	251	224	6	21	33.50892857
1	600	302	276	9	17	33.60144928
1	700	348	322	10	16	33.59627329
1	800	392	365	11	16	33.55616438
1	900	456	426	11	19	33.53755869
1	1000	509	478	12	19	33.4665272
1	1100	574	544	12	18	33.47242647
1	1200	635	606	13	16	33.40924092
1	1300	695	657	14	24	33.40943683
1	1400	779	739	16	24	33.32611637
1	1500	838	792	20	26	33.33459596
1	1600	908	864	21	23	33.35416667
1	1700	971	923	24	24	33.36294691
1	1800	1032	992	25	15	33.29637097
1	1900	1092	1047	26	19	33.2913085
1	2000	1132	1085	26	21	33.26635945
1	2100	1194	1149	27	18	33.29765013
1	2200	1258	1213	27	18	33.30173124
1	2300	1300	1259	28	13	33.28832407
1	2400	1344	1300	30	14	33.28461538
1	2500	1387	1344	30	13	33.33035714
1	2600	1436	1388	30	18	33.3278098
1	2700	1485	1438	33	14	33.36856745
1	2800	1542	1488	35	19	33.36290323
1	2900	1594	1541	35	18	33.4146658
1	3000	1653	1595	36	22	33.42131661
1	3100	1715	1650	37	28	33.43515152
1	3200	1774	1720	40	14	33.42674419
1	3300	1839	1783	40	16	33.3931576
1	3400	1892	1834	40	18	33.39803708
1	3500	1945	1892	40	13	33.42230444
1	3600	2002	1935	40	27	33.41033592
1	3700	2046	1994	44	8	33.44734203
1	3800	2092	2028	44	20	33.43786982

metrics

Figure 21: Metrics after running lb script

episode	time	node	node_capacity	used_resources	ingress_traffic
1	0	pop0	0	0	0
1	0	pop1	7	0	0
1	0	pop2	0	0	0
1	0	pop3	14	0	0
1	0	pop4	7	0	0
1	0	pop5	14	0	0
1	0	pop6	0	0	0
1	0	pop7	0	0	0
1	0	pop8	14	0	0
1	0	pop9	7	0	0
1	0	pop10	7	0	0
1	100	pop0	0	0	6
1	100	pop1	7	5	11
1	100	pop2	0	0	11
1	100	pop3	14	4	10
1	100	pop4	7	4	9
1	100	pop5	14	4	0
1	100	pop6	0	0	0
1	100	pop7	0	0	0
1	100	pop8	14	3	0
1	100	pop9	7	3	0
1	100	pop10	7	2	0
1	200	pop0	0	0	10
1	200	pop1	7	6	14
1	200	pop2	0	0	11
1	200	pop3	14	7	10
1	200	pop4	7	5	5
1	200	pop5	14	5	0
1	200	pop6	0	0	0
1	200	pop7	0	0	0
1	200	pop8	14	4	0
1	200	pop9	7	5	0
1	200	pop10	7	3	0
1	300	pop0	0	0	6
1	300	pop1	7	7	16
1	300	pop2	0	0	7
1	300	pop3	14	5	8
1	300	pop4	7	5	7
1	300	pop5	14	4	0

node_metrics

Figure 22: Node Metrics after running lb script

	A	B	C	D
1	episode	time	node	sf
2	1	0	pop1	a
3	1	0	pop1	b
4	1	0	pop1	c
5	1	0	pop3	a
6	1	0	pop3	b
7	1	0	pop3	c
8	1	0	pop4	a
9	1	0	pop4	b
10	1	0	pop4	c
11	1	0	pop5	a
12	1	0	pop5	b
13	1	0	pop5	c
14	1	0	pop8	a
15	1	0	pop8	b
16	1	0	pop8	c
17	1	0	pop9	a
18	1	0	pop9	b
19	1	0	pop9	c
20	1	0	pop10	a
21	1	0	pop10	b
22	1	0	pop10	c
23	1	100	pop1	b
24	1	100	pop1	a
25	1	100	pop1	c
26	1	100	pop3	a
27	1	100	pop3	b
28	1	100	pop3	c
29	1	100	pop4	a
30	1	100	pop4	b
31	1	100	pop4	c
32	1	100	pop5	a
33	1	100	pop5	b
34	1	100	pop5	c
35	1	100	pop8	a
36	1	100	pop8	b
37	1	100	pop8	c
38	1	100	pop9	a
39	1	100	pop9	b
40	1	100	pop9	c

placements

Figure 23: SF placements after running lb script

episode	time	successful_flows	dropped_flows	total_flows
1	0	0	0	5
1	100	33	0	42
1	200	47	0	50
1	300	41	2	44
1	400	55	0	60
1	500	48	4	50
1	600	52	3	51
1	700	46	1	46
1	800	43	1	44
1	900	61	0	64
1	1000	52	1	53
1	1100	66	0	65
1	1200	62	1	61
1	1300	51	1	60
1	1400	82	2	84
1	1500	53	4	59
1	1600	72	1	70
1	1700	59	3	63
1	1800	69	1	61
1	1900	55	1	60
1	2000	38	0	40
1	2100	64	1	62
1	2200	64	0	64
1	2300	46	1	42
1	2400	41	2	44
1	2500	44	0	43
1	2600	44	0	49
1	2700	50	3	49
1	2800	50	2	57
1	2900	53	0	52
1	3000	54	1	59
1	3100	55	1	62
1	3200	70	3	59
1	3300	63	0	65
1	3400	51	0	53
1	3500	58	0	53
1	3600	43	0	57
1	3700	59	4	44
1	3800	34	0	46

run_flows

Figure 24: Run Flows after running lb script

3.3.3 Shortest Path Results

Results After running the Shortest Path algorithm:

episode	time	total_flows	successful_flows	dropped_flows	in_network_flows	avg_end2end_delay
1	0	5	0	0	5	0
1	100	49	37	0	12	26.2972973
1	200	79	71	0	8	26.45070423
1	300	122	112	0	10	26.33035714
1	400	174	164	0	10	26.83536585
1	500	217	200	0	17	26.74
1	600	257	239	0	18	26.9832636
1	700	305	290	0	15	26.99310345
1	800	333	323	0	10	27.16718266
1	900	384	372	0	12	27.31182796
1	1000	413	406	0	7	27.18226601
1	1100	456	442	0	14	27.30316742
1	1200	503	493	0	10	27.22718053
1	1300	540	530	0	10	27.2509434
1	1400	589	577	0	12	27.34142114
1	1500	616	605	0	11	27.3553719
1	1600	664	655	2	7	27.3480916
1	1700	714	697	2	15	27.32855093
1	1800	756	741	2	13	27.25101215
1	1900	797	787	2	8	27.25794155
1	2000	839	827	2	10	27.22370012
1	2100	892	878	2	12	27.15831435
1	2200	935	920	2	13	27.17065217
1	2300	975	964	2	9	27.19294606
1	2400	1011	994	2	15	27.15191147
1	2500	1060	1041	2	17	27.14505283
1	2600	1105	1095	2	8	27.09954338
1	2700	1149	1136	2	11	27.08010563
1	2800	1200	1190	2	8	27.04453782
1	2900	1230	1222	2	6	27.03355155
1	3000	1286	1272	2	12	27.03144654
1	3100	1335	1318	2	15	27.04172989
1	3200	1389	1372	2	15	27.02623907
1	3300	1447	1429	2	16	27.06438069
1	3400	1497	1480	2	15	27.10540541
1	3500	1553	1535	2	16	27.11596091
1	3600	1621	1603	2	16	27.08671241
1	3700	1671	1651	2	18	27.09206541
1	3800	1732	1708	2	22	27.10772834

metrics

Figure 25: Metrics after running sp script

episode	time	node	node_capacity	used_resources	ingress_traffic
1	0	pop0	0	0	0
1	0	pop1	7	0	0
1	0	pop2	0	0	0
1	0	pop3	14	0	0
1	0	pop4	7	0	0
1	0	pop5	14	0	0
1	0	pop6	0	0	0
1	0	pop7	0	0	0
1	0	pop8	14	0	0
1	0	pop9	7	0	0
1	0	pop10	7	0	0
1	100	pop0	0	0	13
1	100	pop1	7	4	11
1	100	pop2	0	0	6
1	100	pop3	14	6	8
1	100	pop4	7	5	11
1	100	pop5	14	3	0
1	100	pop6	0	0	0
1	100	pop7	0	0	0
1	100	pop8	14	1	0
1	100	pop9	7	4	0
1	100	pop10	7	6	0
1	200	pop0	0	0	7
1	200	pop1	7	4	8
1	200	pop2	0	0	5
1	200	pop3	14	3	7
1	200	pop4	7	4	3
1	200	pop5	14	3	0
1	200	pop6	0	0	0
1	200	pop7	0	0	0
1	200	pop8	14	2	0
1	200	pop9	7	2	0
1	200	pop10	7	3	0
1	300	pop0	0	0	7
1	300	pop1	7	3	7
1	300	pop2	0	0	6
1	300	pop3	14	4	9
1	300	pop4	7	6	14
1	300	pop5	14	2	0

node_metrics

Figure 26: Node Metrics after running sp script

episode	time	node	sf
1	0	pop1	a
1	0	pop1	c
1	0	pop3	a
1	0	pop3	b
1	0	pop4	c
1	0	pop4	b
1	0	pop4	a
1	0	pop5	b
1	0	pop5	c
1	0	pop8	c
1	0	pop9	a
1	0	pop10	b
1	0	pop10	c
1	100	pop1	c
1	100	pop1	a
1	100	pop3	a
1	100	pop3	b
1	100	pop4	c
1	100	pop4	b
1	100	pop4	a
1	100	pop5	b
1	100	pop5	c
1	100	pop8	c
1	100	pop9	a
1	100	pop10	b
1	100	pop10	c
1	200	pop1	c
1	200	pop1	a
1	200	pop3	a
1	200	pop3	b
1	200	pop4	c
1	200	pop4	b
1	200	pop4	a
1	200	pop5	c
1	200	pop5	b
1	200	pop8	c
1	200	pop9	a
1	200	pop10	b
1	200	pop10	c

placements

Figure 27: SF placements after running sp script

episode	time	successful_flows	dropped_flows	total_flows
1	0	0	0	5
1	100	37	0	44
1	200	34	0	30
1	300	41	0	43
1	400	52	0	52
1	500	36	0	43
1	600	39	0	40
1	700	51	0	48
1	800	33	0	28
1	900	49	0	51
1	1000	34	0	29
1	1100	36	0	43
1	1200	51	0	47
1	1300	37	0	37
1	1400	47	0	49
1	1500	28	0	27
1	1600	50	2	48
1	1700	42	0	50
1	1800	44	0	42
1	1900	46	0	41
1	2000	40	0	42
1	2100	51	0	53
1	2200	42	0	43
1	2300	44	0	40
1	2400	30	0	36
1	2500	47	0	49
1	2600	54	0	45
1	2700	41	0	44
1	2800	54	0	51
1	2900	32	0	30
1	3000	50	0	56
1	3100	46	0	49
1	3200	54	0	54
1	3300	57	0	58
1	3400	51	0	50
1	3500	55	0	56
1	3600	68	0	68
1	3700	48	0	50
1	3800	57	0	61

run_flows

Figure 28: Run Flows after running sp script

3.3.4 Service Coordination Quality

First, we compare the achieved solution quality of our proposed algorithms , Random Schedule, Load Balance and Shortest Path. As metrics to evaluate the service coordination quality, we consider the percentage of successfully processed flows and their average end-to-end delay O_d at the end of each experiment as defined in Section 3.1.1 (Mathematical Formulation).

1) Successful Flows: shows the percentage of successful flows achieved by the different algorithms. The percentage of successful flows decreases with increasing load as the network becomes more congested and some flows cannot be processed or forwarded.

2) End-to-end Delay: shows the avg. end-to-end delay of successfully processed flows.

3.3.5 Graph Visualization and algorithms comparisons

In this section we will visualize the CSV files into graphs (using pandas and matplotlib), so we can compare and evaluate the proposed algorithms.

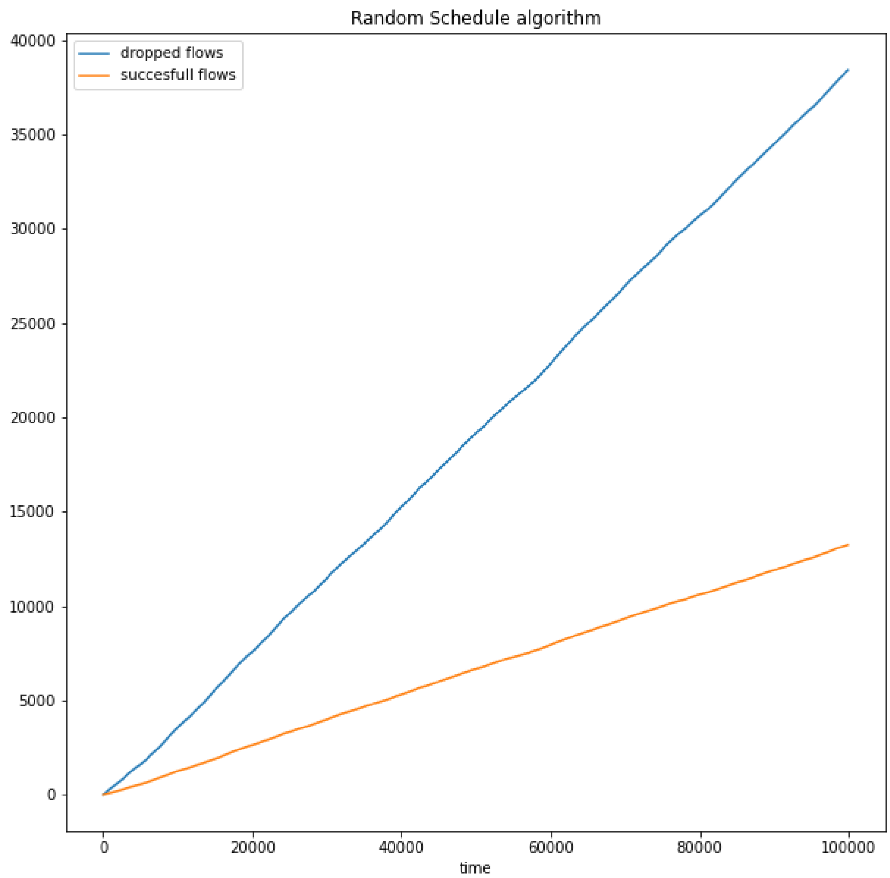

Figure 29: RS successful flows over dropped flows

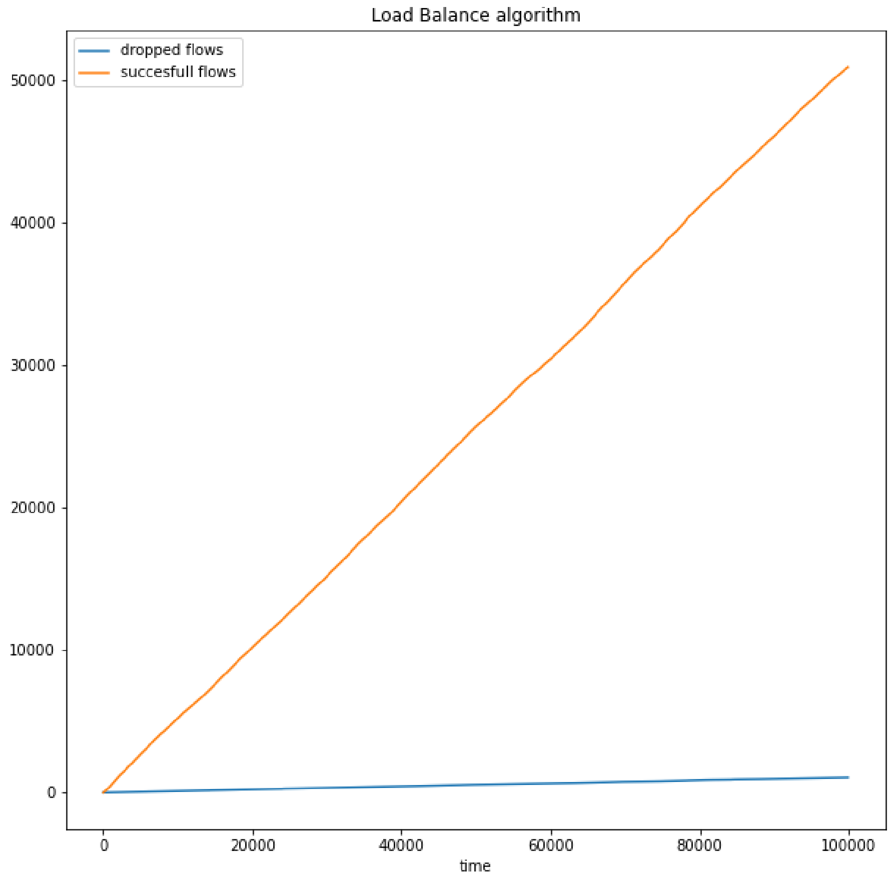

Figure 30: LB successful flows over dropped flows

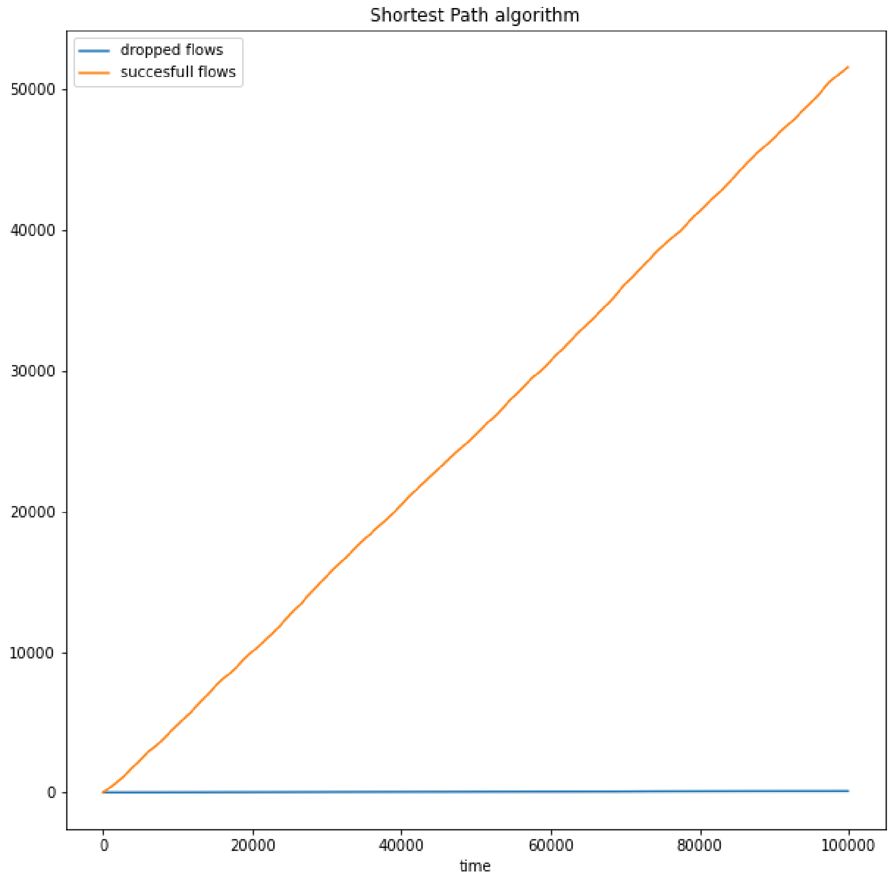

Figure 31: SP successful flows over dropped flows

1. Figures 28,29,30 show the successful flows over dropped flows achieved by three different algorithms. As expected Random Schedule algorithm has the worst results .We can see that the dropped flows are more than the successful ones, which shows that randomness is not a good solution for the thesis subject. With the other two algorithms the results are closer. From the successful over the dropped flows we cannot deduce much, as there is a big gap between them. So let's see only the dropped flows for these two.

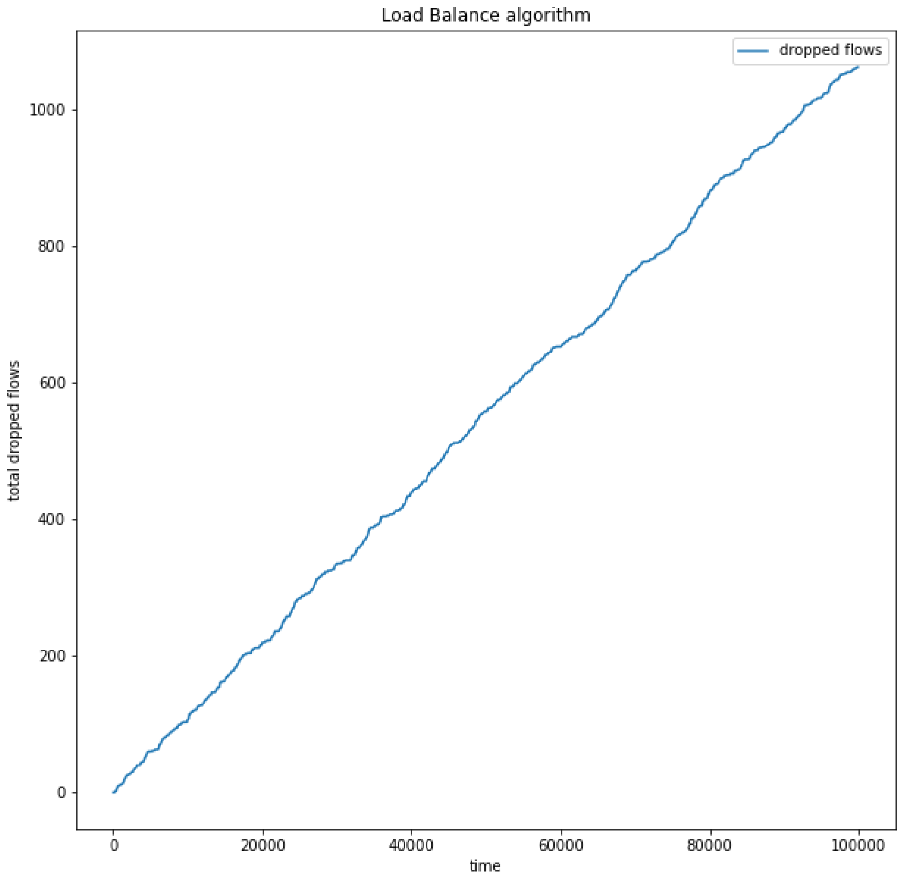

Figure 32: LB dropped flows over time

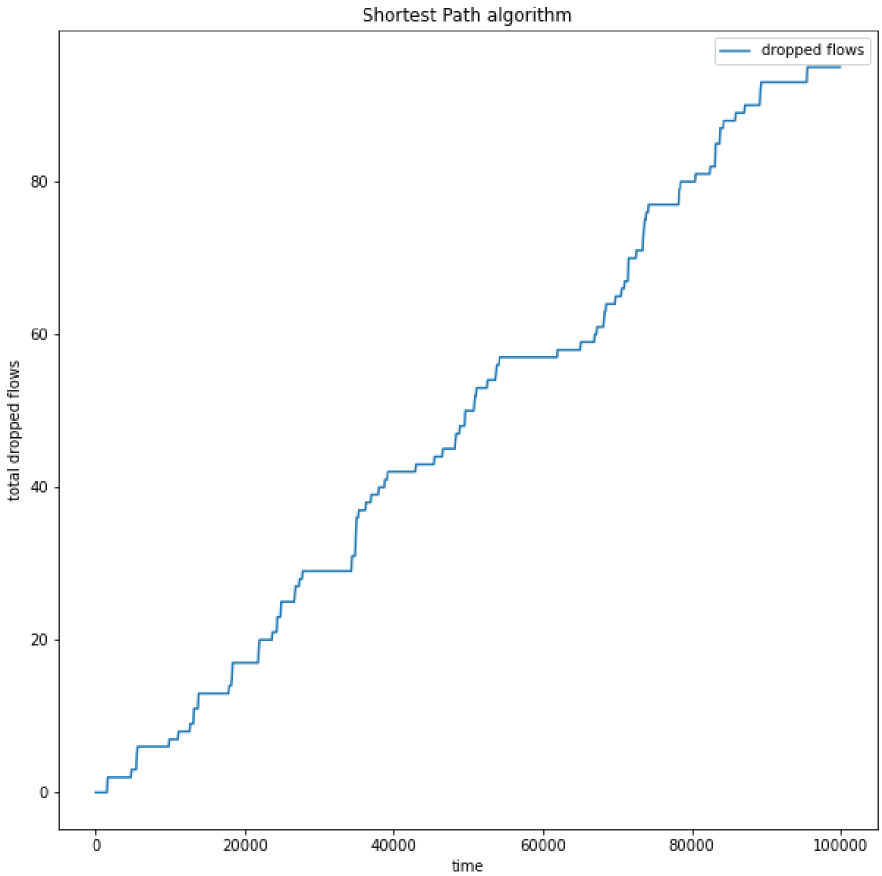

Figure 33: SP dropped flows over time

2. Figures 31, 32 provide a better look on which of these two is more efficient. With the Load Balance algorithm we can see that the total dropped flows over time reached to over 1000, whereas with the Shortest Path the dropped flows do not exceed 100. So we see deduce that regarding the dropped flows , Shortest path algorithm achieves the better results for the simulated environment with the given inputs.

Now let's have a look to the End-to-End delay of the successfully processed flows.

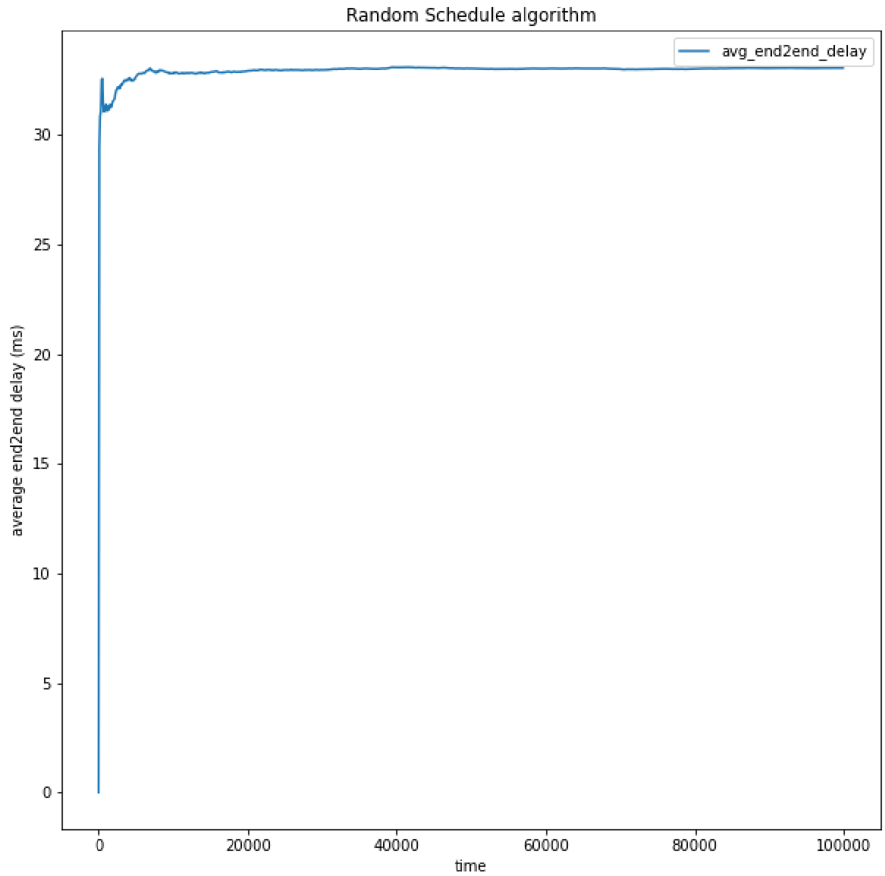

Figure 34: RS successful flows over dropped flows

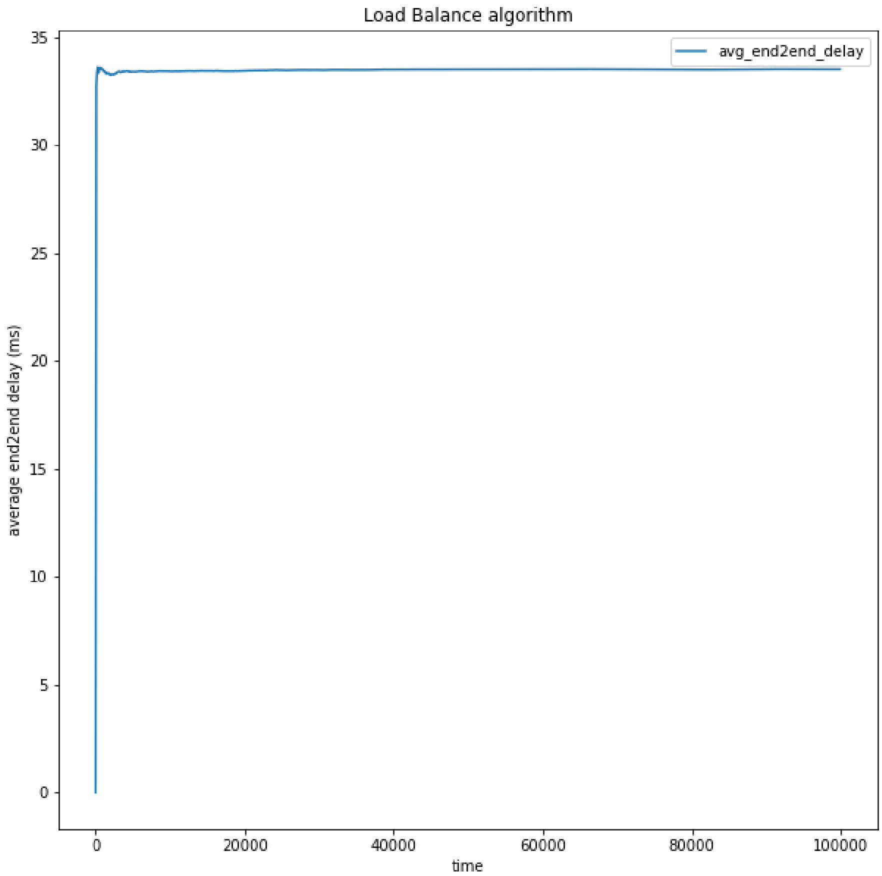

Figure 35: LB successful flows over dropped flows

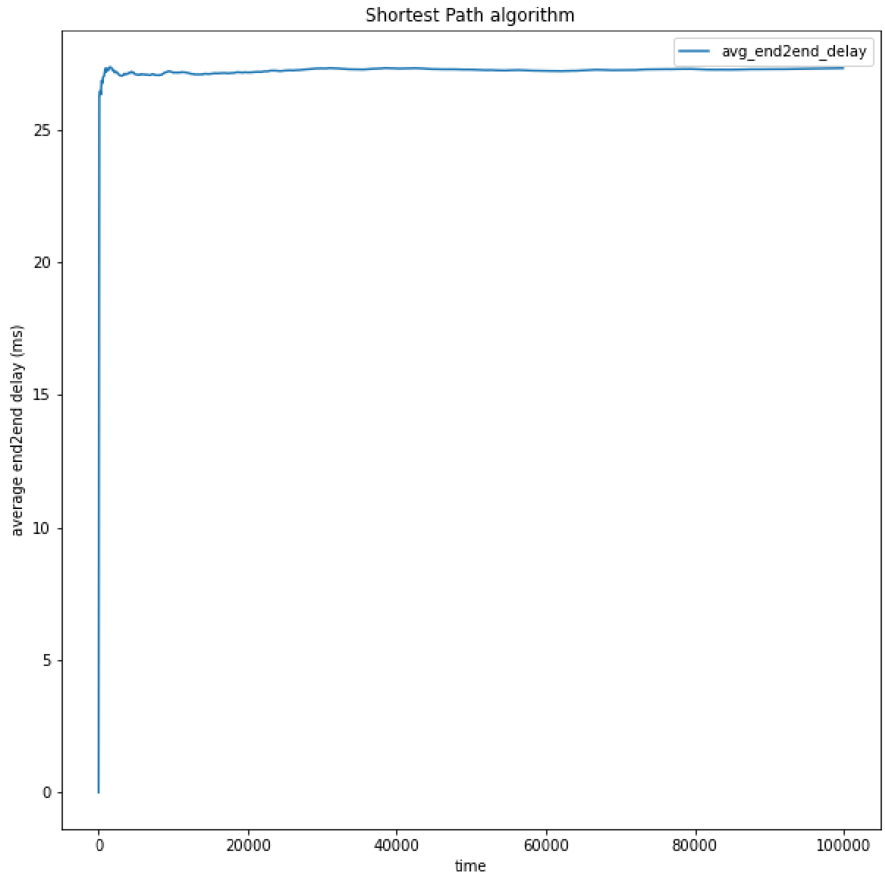

Figure 36: SP successful flows over dropped flows

3. From Figures, 33,34, 35 we see the avg. end-to-end delay of successfully process flows. While Random schedule drops an increasing percentage of flows with increasing load, it ensures lower and constant end-to-end delay for the remaining successful flows comparing to the Load Balance algorithm. For the Shortest path algorithm, avg. end-to-end is optimal comparing to the other two algorithms once more.

Below we will have we see a table that contains the algorithms results along with the time execution:

algorithm	time to execute(minutes:seconds)	average end2end delay(ms)	total dropped flows	total succesful flows
Random Schedule	3:18	32.908	38426	13258
Load Balance	1:04	33.473	1062	50933
Shortest path	1:05	27.209	95	51712

Figure 37: Algorithms results summary

So all in all, Shortest path algorithm achieves far better results for this simulated environment than the other 2, with the suggested configuration.

4 Conclusions

We show how an algorithmic approach can be used to automatically solve the coordination of chained VNFs under realistic conditions. The proposed scheme was to develop algorithms on a simulated environment. We used a Real network topology (Abilene) that is representative of a small-scale network with 11 nodes and 14 links as input. The simulated environment was implemented in Python 3.8 with SimPy framework running on a Linux system (Ubuntu distribution) , in order to produce we produced a discrete-event flow-based simulator which a fast testbed for VNF coordination algorithms. At the same time, we saw that this setup require less or no global network information, and can be massively run algorithms in parallel, is robust to failures. We compared three algorithms (Random Schedule, Shortest Path and Load Balance) that were applied in the simulated for the solution of the thesis problem and we concluded that the Shortest Path achieves the best results out of the three with the Load Balance algorithm coming second. The experimental results, which have been carried out through , demonstrate how the proposed method can have an impact in a more automated SF coordination without manual actions. We believe that an algorithmic approach can significantly improve service coordination and resulting QoS in practice.

5 Future directions

In future work, we can investigate more algorithms to implement in this environment and even an AI/ ML-oriented (Artificial Intelligence) decision making approach. As well, we can look in hybrid approaches, where some coordination decisions are made centrally and others in a distributed manner.

But one thing is for sure , automation can help us find solutions to the VNF related problems , so that in the future the QoS that Operators need to achieve, to be optimized and the costs to be minimized.

References

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A´ Manual on how to install the environment and execute the algorithms

In order to execute the subject's experiment we used the following GitHub directories:
https://github.com/RealVNF/coord-sim
https://github.com/RealVNF/common-utils
https://github.com/kopsa95/baseline-algorithms

coord-sim: We need this in order to Simulate flow-level, inter-node network coordination including scaling and placement of services and scheduling/balancing traffic between them

common-utils: This is the Interface definition between the algorithms and environments.

Baseline-Algorithms: Includes baseline algorithms for coordination of service mesh consisting of multiple microservices. Includes Non-RL algorithms (Random Schedule, Shortest Path and Load Balance).

Setup: First ,via git we exported the directory with the algorithms we proposed: git clone https://github.com/kopsa95/baseline-algorithms

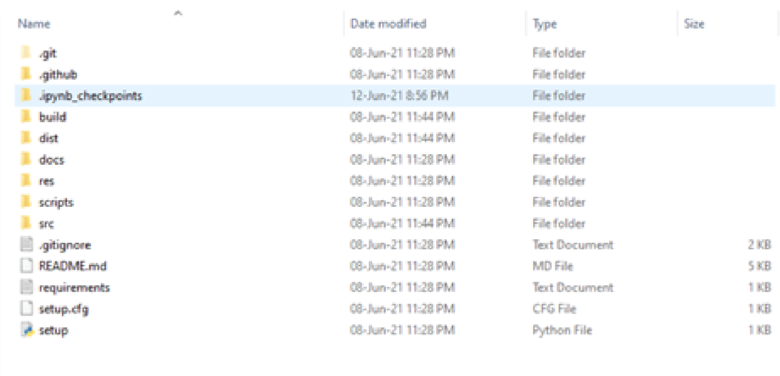
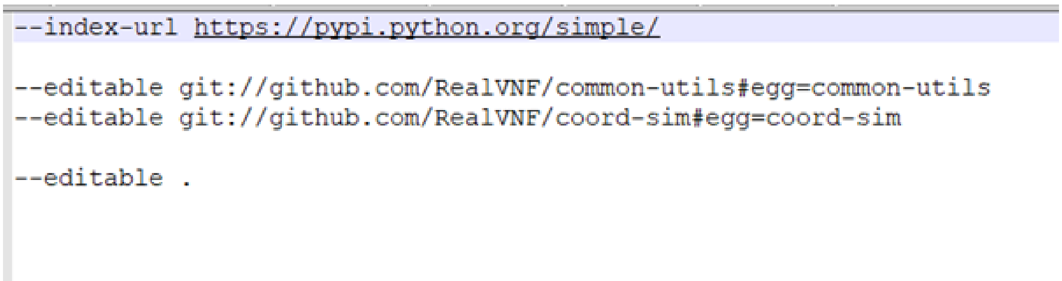


Figure 38: baseline algorithms directory structure

Under /res directory we have the inputs that we will use in order to simulate the experiments (the network graph, and the configuration of the simulation). Under /src we have the algorithms that we used.

Then in order to install the above package we used Python 3.8 as the project was implemented in Python.

We install the requirements.txt file via:
python3 -m pip install -r requirements.txt



```
--index-url https://pypi.python.org/simple/

--editable git://github.com/RealVNF/common-utils#egg=common-utils
--editable git://github.com/RealVNF/coord-sim#egg=coord-sim

--editable .
```

Figure 39: txt file that shows the requirements

This will add the other 2 GitHub directories under: C:/Users/<user>/<GithubPath>/baseline-algorithms/src

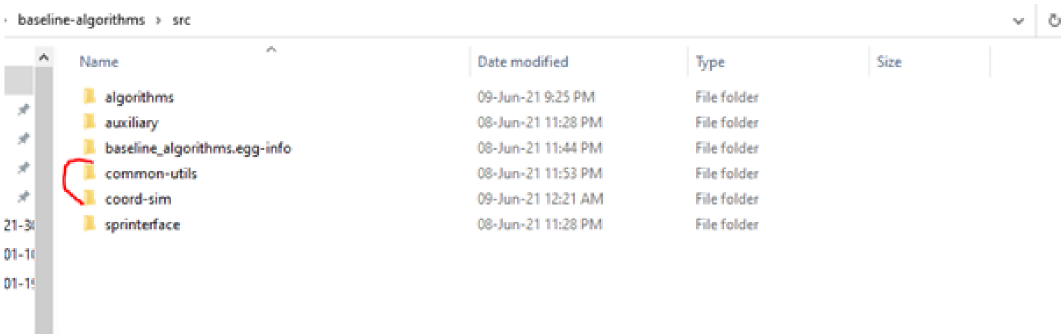


Figure 40: 2 new directories added under /src

Then we will go these directories via cd (change directory command) and install the setup.py file of each folder.

The Setup.py for coord-sim installs the following pacakges:

```python
from setuptools import setup, find_packages
requirements = [
    'simpy>=4',
    'networkx==2.4',
    'geopy',
    'pyyaml>=5.1',
    'common-utils',
    'cython',   # otherwise sklearn fails
    'sklearn',
    'pandas',
    'tensorflow>=1.14.0',
    'keras==2.2.5',
    'matplotlib',
]

test_requirements = [
    'flake8',
    'nose2'
]

dependency_links = [
    'git+https://github.com/RealVNF/common-utils'
]

setup(
    name='coord-sim',
    version='2.1.0',
    description='Simulate flow-level, inter-node network coordination including scaling and placement of services and '
                'scheduling/balancing traffic between them.',
    url='https://github.com/RealVNF/coord-sim',
    author='Stefan Schneider',
    dependency_links=dependency_links,
    author_email='stefan.schneider@upb.de',
    package_dir={'': 'src'},
    packages=find_packages('src'),
    install_requires=requirements + test_requirements,
    tests_require=test_requirements,
    zip_safe=False,
    entry_points={
        'console_scripts': [
            'coord-sim=coordsim.main:main',
            'animation=animations.animations:main',
            'lstm-predict=coordsim.traffic_predictor.lstm_predictor:main'
        ],
    },
)
```

Figure 41: setup.py of coord-sim package

The Setup.py for common-utils installs the following pacakges:

```python
# -*- coding: utf-8 -*-
from setuptools import setup, find_packages


requirements = [
    'networkx==2.4',
    'PyYAML',
    'numpy>=1.16.5,<=1.19.5'
]

test_requirements = [
    'flake8'
]


setup(
    name='common-utils',
    version='1.0.1',
    author="RealVNF",
    description="Interface definition between coordination algorithms and environments. "
                "Includes a dummy environment.",
    url='https://github.com/RealVNF/common-utils',
    package_dir={'': 'src'},
    packages=find_packages('src'),
    install_requires=requirements + test_requirements,
    tests_require=test_requirements,
    zip_safe=False,
)
```

Figure 42: setup.py of common-utils package

And then we install the baseline-algorithms setup.py:

```python
# -*- coding: utf-8 -*-
import os

from setuptools import setup, find_packages

requirements = [
    'tqdm',
    'common-utils',
    'coord-sim'
]

test_requirements = [
    'flake8'
]

setup(
    name='baseline-algorithms',
    version='1.0.1',
    description="Baseline algorithms for coordination of chained VNFs",
    url='https://github.com/RealVNF/baseline-algorithms',
    package_dir={'': 'src'},
    packages=find_packages('src'),
    install_requires=requirements + test_requirements,
    tests_require=test_requirements,
    zip_safe=False,
    entry_points={
        'console_scripts': [
            "rs=algorithms.randomSchedule:main",
            "lb=algorithms.loadBalance:main",
            "sp=algorithms.shortestPath:main"
        ],
    },
)
```

Figure 43: setup.py of load-balance package

Command used for the installation of the above:
python3 setup.py install (in each path)

Packages and short description:

- **networkx:** NetworkX is a Python package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks.
- **PyYAML:** YAML is a data serialization format designed for human readability and interaction with scripting languages. PyYAML is a YAML parser and emitter for Python. PyYAML features a complete YAML 1.1 parser, Unicode support, pickle support, capable extension API, and sensible error messages. PyYAML supports standard YAML tags and provides Python-specific tags that allow to represent an arbitrary Python object. PyYAML is applicable for

a broad range of tasks from complex configuration files to object serialization and persistence.

- **NumPy:** NumPy is the fundamental package for scientific computing in Python. It is a Python library that provides a multidimensional array object, various derived objects (such as masked arrays and matrices), and an assortment of routines for fast operations on arrays, including mathematical, logical, shape manipulation, sorting, selecting, I/O, discrete Fourier transforms, basic linear algebra, basic statistical operations, random simulation and much more.

- **Tqdm:** Instantly make your loops show a smart progress meter - just wrap any iterable with tqdm(iterable), and you're done!

- **SimPy:** SimPy is a process-based discrete-event simulation framework based on standard Python.

- **Geopy:** geopy is a Python client for several popular geocoding web services. geopy makes it easy for Python developers to locate the coordinates of addresses, cities, countries, and landmarks across the globe using third-party geocoders and other data sources.

- **Cython:** Cython is an optimising static compiler for both the Python programming language and the extended Cython programming language (based on Pyrex). It makes writing C extensions for Python as easy as Python itself.

- **Scikit-learn (not used for this project):** Scikit-learn is probably the most useful library for machine learning in Python. The sklearn library contains a lot of efficient tools for machine learning and statistical modeling including classification, regression, clustering and dimensionality reduction.

- **Tensorflow(not used for this project):** TensorFlow is an end-to-end open source platform for machine learning. It has a comprehensive, flexible ecosystem of tools, libraries, and community resources that lets researchers push the state-of-the-art in ML and developers easily build and deploy ML-powered applications.

- **Keras (not used in this project):** Keras is an API designed for human beings, not machines. Keras follows best practices for reducing cognitive load: it offers consistent and simple APIs, it minimizes the number of user actions required for common use cases, and it provides clear and actionable error messages. It also has extensive documentation and developer guides.

- **Matplotlib:** Matplotlib is a comprehensive library for creating static, animated, and interactive visualizations in Python.

When the setup is ready we are ready to apply our algorithms.

Algorithms used for running the proposed scripts: can be found at https://github.com/kopsa95/baseline-algorithms/tree/master/src/algorithms

RandomSchedule.py

```
import argparse
import logging
import os
import random
from collections import defaultdict
from datetime import datetime
from pathlib import Path
from random import uniform

from common.common_functionalities import
    normalize_scheduling_probabilities , \
    get_ingress_nodes_and_cap, copy_input_files , create_input_file
# for use with the flow-level simulator https :// github .com/RealVNF/
    coordination-simulation ( after installation )
from siminterface . simulator import Simulator
from spinterface import SimulatorAction
from tqdm import tqdm

log = logging . getLogger(__name__)
DATETIME = datetime.now().strftime("%Y-%m-%d_%H-%M-%S")
PROJECT_ROOT = str(Path(__file__).parent.parent. parent )


def get_placement( nodes_list , sf_list ):
    """ places each sf in each node of the network
    Parameters:
        nodes_list
        sf_list
    Returns:
        a Dictionary with:
            key = nodes of the network
            value = list of all the SFs in the network
    """
    placement = defaultdict ( list )
    for node in nodes_list :
        placement[node] = sf_list
```

```
    return placement


def get_schedule(nodes_list, sf_list, sfc_list):
    """ return a dict of schedule for each node of the network
    for each node in the network, we generate floating point random
        numbers in the range 0 to 1
         '''
        Schedule is of the following form:
            schedule : dict
                {
                    'node id' : dict
                    {
                        'SFC id' : dict
                        {
                            'SF id' : dict
                            {
                                'node id' : float (Inclusive of zero
                                    values)
                            }
                        }
                    }
                }
         '''
    Parameters:
         nodes_list
         sf_list
         sfc_list
    Returns:
         schedule of the form shown above
    """
    schedule = defaultdict(lambda: defaultdict(lambda: defaultdict(
        lambda: defaultdict(float))))
    for outer_node in nodes_list:
        for sfc in sfc_list:
            for sf in sf_list:
                # this list may not sum to 1
                random_prob_list = [uniform(0, 1) for _ in range(len(
                    nodes_list))]
                # Because of floating point precision (.59 + .33 + .08)
                    can be equal to .99999999
                # So we correct the sum only if the absolute diff. is
```

```
            more than  a  tolerance (0.0000000149011611938476 56)
        random_prob_list  =  normalize_scheduling_probabilities  (
            random_prob_list)
        for  inner_node  in  nodes_list :
            if  len(random_prob_list)  !=  0:
                schedule[outer_node][ sfc ][ sf ][inner_node]  =
                    random_prob_list.pop()
            else :
                schedule[outer_node][ sfc ][ sf ][inner_node]  = 0
    return  schedule


def  parse_args () :
    parser  =  argparse . ArgumentParser( description ="Dummy Coordinator")
    parser . add_argument('−i' ,  '−− iterations ' ,  required=False ,  default =10,
         dest=" iterations " ,  type=int)
    parser . add_argument('−s' ,  '−−seed' ,  required=False ,  default =9999,
        dest="seed" ,  type=int)
    parser . add_argument('−n' ,  '−−network' ,  required=True,  dest='network')
    parser . add_argument('−sf' ,  '−− service_functions ' ,  required=True,  dest
        =" service_functions ")
    parser . add_argument('−c' ,  '−−config' ,  required=True,  dest="config")
    return  parser . parse_args ()


def  main():
    # Parse  arguments
    args  =  parse_args ()
    if  not  args . seed:
        args . seed  = random.randint (1,  9999)
    logging . basicConfig ( level =logging . INFO)
    logging . getLogger("coordsim"). setLevel (logging . WARNING)

    # Creating  the  results  directory  variable  where the  simulator  result
        files  will  be  written
    network_stem = os . path .  splitext  (os . path . basename(args.network)) [0]
    service_function_stem  = os . path .  splitext  (os . path . basename(args.
        service_functions  )) [0]
    simulator_config_stem  = os . path .  splitext  (os . path . basename(args . config
        )) [0]

    results_dir  = f"{PROJECT_ROOT}/results/{network_stem}/{
```

```
        service_function_stem}/{simulator_config_stem}" \
                f"/{DATETIME}_seed{args.seed}"

    # creating the simulator
    simulator = Simulator(os.path.abspath(args.network),
                          os.path.abspath(args.service_functions),
                          os.path.abspath(args.config), test_mode=True,
                              test_dir = results_dir)
    init_state = simulator.init(args.seed)
    log.info("Network Stats after init(): %s", init_state.network_stats)
    nodes_list = [node['id'] for node in init_state.network.get('nodes')]
    sf_list = list(init_state.service_functions.keys())
    sfc_list = list(init_state.sfcs.keys())
    ingress_nodes = get_ingress_nodes_and_cap(simulator.network)
    # we place every sf in each node of the network, so placement is
        calculated only once
    placement = get_placement(nodes_list, sf_list)
    # iterations define the number of time we wanna call apply()
    log.info(f"Running for {args.iterations} iterations ...")
    for i in tqdm(range(args.iterations)):
        schedule = get_schedule(nodes_list, sf_list, sfc_list)
        action = SimulatorAction(placement, schedule)
        _ = simulator.apply(action)

    # We copy the input files (network, simulator config ....) to the
        results directory
    copy_input_files(results_dir, os.path.abspath(args.network), os.path.
        abspath(args.service_functions),
                     os.path.abspath(args.config))
    # Creating the input file in the results directory containing the
        num_ingress and the Algo used attributes
    create_input_file(results_dir, len(ingress_nodes), "Rand")
    log.info(f"Saved results in {results_dir}")


if __name__ == '__main__':
    main()
```

loadBalance.py

```
import argparse
import logging
import os
import random
from collections import defaultdict
from datetime import datetime
from pathlib import Path

from common.common_functionalities import
    normalize_scheduling_probabilities , create_input_file ,
    copy_input_files , \
    get_ingress_nodes_and_cap
from siminterface . simulator import Simulator
from spinterface import SimulatorAction
from tqdm import tqdm

log = logging . getLogger(__name__)
DATETIME = datetime.now().strftime("%Y−%m−%d_%H−%M−%S")
PROJECT_ROOT = str(Path(__file__).parent.parent. parent )


def get_placement( nodes_list , sf_list ):
    """ places each sf on each node of the network with some capacity
    Parameters:
        nodes_list
        sf_list
    Returns:
        a Dictionary with:
            key = nodes of the network
            value = list of all the SFs on the node
    """
    placement = defaultdict ( list )
    for node in nodes_list :
        placement[node] = sf_list
    return placement


def get_schedule( nodes_list , nodes_with_cap, sf_list , sfc_list ):
    """ return a dict of schedule for each node of the network
        '''
        Schedule is of the following form:
```

```
        schedule : dict
            {
                'node id' : dict
                {
                    'SFC id' : dict
                    {
                        'SF id' : dict
                        {
                            'node id' : float (Inclusive of zero
                                values)
                        }
                    }
                }
            }
    '''
Parameters:
    nodes_list
    sf_list
    sfc_list
Returns:
    schedule of the form shown above
"""
schedule = defaultdict(lambda: defaultdict(lambda: defaultdict(
    lambda: defaultdict(float))))
for outer_node in nodes_list:
    for sfc in sfc_list:
        for sf in sf_list:
            # all 0's list
            uniform_prob_list = [0 for _ in range(len(nodes_with_cap)
                )]
            # Uniformly distributing the schedules between all nodes
            uniform_prob_list = normalize_scheduling_probabilities(
                uniform_prob_list)
            for inner_node in nodes_list:
                if inner_node in nodes_with_cap:
                    schedule[outer_node][sfc][sf][inner_node] =
                        uniform_prob_list.pop()
                else:
                    schedule[outer_node][sfc][sf][inner_node] = 0
return schedule
```

```
def parse_args():
    parser = argparse.ArgumentParser(description="Load Balance Algorithm"
        )
    parser.add_argument('-i', '--iterations', required=False, default=10,
         dest="iterations", type=int)
    parser.add_argument('-s', '--seed', required=False, dest="seed", type
        =int)
    parser.add_argument('-n', '--network', required=True, dest='network')
    parser.add_argument('-sf', '--service_functions', required=True, dest
        ="service_functions")
    parser.add_argument('-c', '--config', required=True, dest="config")
    return parser.parse_args()


def main():
    # Parse arguments
    args = parse_args()
    if not args.seed:
        args.seed = random.randint(1, 9999)
    logging.basicConfig(level=logging.WARNING)
    logging.getLogger("coordsim").setLevel(logging.WARNING)

    # Creating the results directory variable where the simulator result
        files will be written
    network_stem = os.path.splitext(os.path.basename(args.network))[0]
    service_function_stem = os.path.splitext(os.path.basename(args.
        service_functions))[0]
    simulator_config_stem = os.path.splitext(os.path.basename(args.config
        ))[0]

    results_dir = f"{PROJECT_ROOT}/results/{network_stem}/{
        service_function_stem}/{simulator_config_stem}" \
                  f"/{DATETIME}_seed{args.seed}"

    # creating the simulator
    simulator = Simulator(os.path.abspath(args.network),
                          os.path.abspath(args.service_functions),
                          os.path.abspath(args.config), test_mode=True,
                              test_dir=results_dir)
    init_state = simulator.init(args.seed)
    log.info("Network Stats after init(): %s", init_state.network_stats)
    nodes_list = [node['id'] for node in init_state.network.get('nodes')]
```

```
    nodes_with_capacity = []
    for node in simulator.network.nodes(data=True):
        if node[1]['cap'] > 0:
            nodes_with_capacity.append(node[0])
    sf_list = list( init_state . service_functions .keys())
    sfc_list = list( init_state . sfcs .keys())
    ingress_nodes = get_ingress_nodes_and_cap( simulator .network)
    # we place every sf on each node of the network with some capacity,
        so placement is calculated only once
    placement = get_placement( nodes_with_capacity, sf_list )
    # Uniformly distributing the schedule for all Nodes with some
        capacity
    schedule = get_schedule( nodes_list , nodes_with_capacity, sf_list ,
        sfc_list )
    # Since the placement and the schedule are fixed , the action would
        also be the same throughout
    action = SimulatorAction(placement, schedule)
    # iterations define the number of time we wanna call apply()
    log.info(f"Running for {args. iterations } iterations ... ")
    for i in tqdm(range(args. iterations )):
        _ = simulator.apply(action)
    # We copy the input files (network, simulator config ....) to the
        results directory
    copy_input_files ( results_dir , os.path.abspath(args.network), os.path.
        abspath(args. service_functions ),
                          os.path.abspath(args.config))
    # Creating the input file in the results directory containing the
        num_ingress and the Algo used attributes
    create_input_file ( results_dir , len(ingress_nodes), "LB")
    log.info(f"Saved results in { results_dir }")


if __name__ == '__main__':
    main()
```

shortestPath.py

```
import argparse
import logging
import os
import random
from collections import defaultdict
from datetime import datetime
from pathlib import Path

from common.common_functionalities import
    normalize_scheduling_probabilities , create_input_file , \
    copy_input_files , get_ingress_nodes_and_cap
from siminterface . simulator import Simulator
from spinterface import SimulatorAction
from tqdm import tqdm

log = logging . getLogger(__name__)
DATETIME = datetime.now().strftime("%Y-%m-%d_%H-%M-%S")
PROJECT_ROOT = str(Path(__file__).parent.parent. parent )


def get_closest_neighbours (network, nodes_list ):
    """
    Finding the closest neighbours to each node in the network. For each
        node of the network we maintain a list of
    neighbours sorted in increasing order of distance to it .
    params:
        network: A networkX graph
        nodes_list : a list of nodes in the Network
    Returns:
        closest_neighbour : A dict containing lists of closest neighbour
            to each node in the network sorted in
                            increasing order to distance .
    """

    all_pair_shortest_paths = network.graph[' shortest_paths ']
    closest_neighbours = defaultdict ( list )
    for source in nodes_list :
        neighbours = defaultdict (int)
        for dest in nodes_list :
            if source != dest:
```

```
                delay = all_pair_shortest_paths [(source, dest)][1]
                neighbours[dest] = delay
        sorted_neighbours = [k for k, v in sorted(neighbours.items(), key
            =lambda item: item[1])]
        closest_neighbours [source] = sorted_neighbours
    return closest_neighbours


def next_neighbour(index, num_vnfs_filled, node, placement,
    closest_neighbours , sf_list , nodes_cap):
    """
    Finds the next available neighbour to the index node
    Args:
        index: closest neighbours of 'node' is a list , index tells which
            closest neighbour to start looking from
        num_vnfs_filled: Tells the number of VNFs present on all nodes e.
            g: every node in the network has atleast 1 VNF,
                        some might have more than that. This tells us
                            the minimum every node has
        node: The node whose closest neighbour is to be found
        placement: placeement of VNFs in the entire network
        closest_neighbours: neighbours of each node in the network in the
            increasing order of distance
        sf_list : The VNFs in the network
        nodes_cap: Capacity of each node in the network
    Returns:
            The next closest neighbour of the requested node that:
            - has some capacity
            - while some of the nodes in the network have 0 VNFs it
                returns the closest neighbour that has 0 VNFs,
              If some nodes in the network has just 1 VNF, it returns the
                    closest neighbour with just 1 VNF and so on
    """
    while len(placement[closest_neighbours [node][index]]) >
        num_vnfs_filled[0] or \
            nodes_cap[closest_neighbours [node][index]] == 0:
        index += 1
        if index == len(closest_neighbours [node]):
            num_vnfs_filled[0] += 1
            index = 0
        if num_vnfs_filled[0] > len(sf_list):
            index = 0
```

```
            break
    return index


def get_placement_schedule(network, nodes_list, sf_list, sfc_list,
    ingress_nodes, nodes_cap):
    """
        '''
        Schedule is of the following form:
            schedule : dict
                {
                    'node id' : dict
                    {
                        'SFC id' : dict
                        {
                            'SF id' : dict
                            {
                                'node id' : float (Inclusive of zero
                                    values)
                            }
                        }
                    }
                }
        '''
    Parameters:
        network: A NetworkX object
        nodes_list: all the nodes in the network
        sf_list: all the sf's in the network
        sfc_list: all the SFCs in the network, right now assuming to be
            just 1
        ingress_nodes: all the ingress nodes in the network
        nodes_cap: Capacity of each node in the network
    Returns:
        - a placement Dictionary with:
              key = nodes of the network
              value = list of all the SFs in the network
        - schedule of the form shown above
    """
    placement = defaultdict(list)
    schedule = defaultdict(lambda: defaultdict(lambda: defaultdict(
        lambda: defaultdict(float))))
    # Initializing the schedule for all nodes, for all SFs to 0
```

```
for src in nodes_list :
    for sfc in sfc_list :
        for sf in sf_list :
            for dstn in nodes_list :
                schedule[src][sfc][sf][dstn] = 0
# Getting the closest neighbours to each node in the network
closest_neighbours = get_closest_neighbours(network, nodes_list)

# - For each Ingress node of the network we start by placing the
    first VNF of the SFC on it and then place the
# 2nd VNF of the SFC on the closest neighbour of the Ingress, then
    the 3rd VNF on the closest neighbour of the node
# where we placed the 2nd VNF and so on.
# - The closest neighbour is chosen based on the following criteria :
#   - while some nodes in the network has 0 VNFs, the closest
    neighbour cannot be an Ingress node
#   - The closest neighbour must have some capacity
#   - while some of the nodes in the network have 0 VNFs it chooses
    the closest neighbour that has 0 VNFs,
#     If some nodes in the network has just 1 VNF, it returns the
    closest neighbour with just 1 VNF and so on
for ingress in ingress_nodes:
    node = ingress
    # We choose a list with just one element because a list is
        mutable in python and we want 'next_neighbour'
    # function to change the value of this variable
    num_vnfs_filled = [0]
    # Placing the 1st VNF of the SFC on the ingress nodes if the
        ingress node has some capacity
    # Otherwise we find the closest neighbour of the Ingress that has
        some capacity and place the 1st VNF on it
    if nodes_cap[ingress] > 0:
        if sf_list[0] not in placement[node]:
            placement[node].append(sf_list[0])
        schedule[node][sfc_list[0]][sf_list[0]][node] += 1
    else:
        # Finding the next neighbour which is not an ingress node and
            has some capacity
        index = next_neighbour(0, num_vnfs_filled, ingress, placement
            , closest_neighbours, sf_list, nodes_cap)
        while num_vnfs_filled[0] == 0 and closest_neighbours[ingress
            ][index] in ingress_nodes:
```

```
            if index + 1 >= len( closest_neighbours [ ingress ]) :
                break
            index = next_neighbour(index + 1, num_vnfs_filled ,
                ingress , placement, closest_neighbours ,
                                        sf_list , nodes_cap)
        node = closest_neighbours [ ingress ][ index ]
        if sf_list [0] not in placement[node]:
            placement[node].append( sf_list [0])
        schedule[ ingress ][ sfc_list [0]][ sf_list [0]][ node] += 1

    # For the remaining VNFs in the SFC we look for the closest
        neighbour and place the VNFs on them
    for j in range(len( sf_list ) − 1):
        index = next_neighbour(0, num_vnfs_filled , node, placement,
            closest_neighbours , sf_list , nodes_cap)
        while num_vnfs_filled [0] == 0 and closest_neighbours [node][
            index] in ingress_nodes :
            if index + 1 >= len( closest_neighbours [node]) :
                break
            index = next_neighbour(index + 1, num_vnfs_filled , node,
                placement, closest_neighbours ,
                                        sf_list , nodes_cap)
        new_node = closest_neighbours [node][index]
        if sf_list [j + 1] not in placement[new_node]:
            placement[new_node].append( sf_list [j + 1])
        schedule[node][ sfc_list [0]][ sf_list [j + 1]][new_node] += 1
        node = new_node

# Since the sum of schedule probabilities for each SF of each node
    may not be 1 , we make it 1 using the
# ' normalize_scheduling_probabilities ' function .
for src in nodes_list :
    for sfc in sfc_list :
        for sf in sf_list :
            unnormalized_probs_list = list (schedule[ src ][ sfc ][ sf ].
                values () )
            normalized_probs = normalize_scheduling_probabilities (
                unnormalized_probs_list )
            for i in range(len( nodes_list )) :
                schedule[ src ][ sfc ][ sf ][ nodes_list [ i ]] =
                    normalized_probs[ i ]
return placement, schedule
```

```
def parse_args():
    parser = argparse.ArgumentParser(description="Load Balance Algorithm"
        )
    parser.add_argument('-i', '--iterations', required=False, default=10,
          dest="iterations", type=int)
    parser.add_argument('-s', '--seed', required=False, dest="seed", type
        =int)
    parser.add_argument('-n', '--network', required=True, dest='network')
    parser.add_argument('-sf', '--service_functions', required=True, dest
        ="service_functions")
    parser.add_argument('-c', '--config', required=True, dest="config")
    return parser.parse_args()


def main():
    # Parse arguments
    args = parse_args()
    if not args.seed:
        args.seed = random.randint(1, 9999)
    logging.basicConfig(level=logging.WARNING)
    logging.getLogger("coordsim").setLevel(logging.WARNING)

    # Creating the results directory variable where the simulator result
        files will be written
    network_stem = os.path.splitext(os.path.basename(args.network))[0]
    service_function_stem = os.path.splitext(os.path.basename(args.
        service_functions))[0]
    simulator_config_stem = os.path.splitext(os.path.basename(args.config
        ))[0]

    results_dir = f"{PROJECT_ROOT}/results/{network_stem}/{
        service_function_stem}/{simulator_config_stem}" \
                  f"/{DATETIME}_seed{args.seed}"

    # creating the simulator
    simulator = Simulator(os.path.abspath(args.network),
                          os.path.abspath(args.service_functions),
                          os.path.abspath(args.config), test_mode=True,
                              test_dir=results_dir)
    init_state = simulator.init(args.seed)
```

```
    log.info("Network Stats after init(): %s", init_state.network_stats)
    nodes_list = [node['id'] for node in init_state.network.get('nodes')]
    sf_list = list(init_state.service_functions.keys())
    sfc_list = list(init_state.sfcs.keys())
    ingress_nodes, nodes_cap = get_ingress_nodes_and_cap(simulator.
        network, cap=True)
    # getting the placement and schedule
    placement, schedule = get_placement_schedule(simulator.network,
         nodes_list, sf_list, sfc_list, ingress_nodes,
                                                         nodes_cap)
    # Since the placement and the schedule are fixed , the action would
        also be the same throughout
    action = SimulatorAction(placement, schedule)
    # iterations define the number of time we wanna call apply(); use
        tqdm for progress bar
    log.info(f"Running for {args.iterations} iterations ...")
    for i in tqdm(range(args.iterations)):
        _ = simulator.apply(action)
    # We copy the input files (network, simulator config ....) to the
         results directory
    copy_input_files(results_dir, os.path.abspath(args.network), os.path.
        abspath(args.service_functions),
                     os.path.abspath(args.config))
    # Creating the input file in the results directory containing the
        num_ingress and the Algo used attributes
    create_input_file(results_dir, len(ingress_nodes), "SP")
    log.info(f"Saved results in {results_dir}")


if __name__ == '__main__':
    main()
```

Usage of the commands:

Usage

```
usage: rs [-h] [-i ITERATIONS] [-s SEED] -n NETWORK -sf
                   SERVICE_FUNCTIONS -c CONFIG

Dummy Coordinator

optional arguments:
  -h, --help            show this help message and exit
  -i ITERATIONS, --iterations ITERATIONS
  -s SEED, --seed SEED
  -n NETWORK, --network NETWORK
  -sf SERVICE_FUNCTIONS, --service_functions SERVICE_FUNCTIONS
  -c CONFIG, --config CONFIG
```

Figure 44: How to call each algorithm in CLI

When the algorithm-scripts are ran , this should be shown in the console:

```
8. WSL-Ubuntu    10. WSL-Ubuntu
INFO:siminterface.simulator:Not enough capacity for flow 51736 at node pop0. Dropping flow.
INFO:siminterface.simulator:Flow 51731 started travelling on edge (pop8, pop5)
INFO:siminterface.simulator:Flow 51728 started travelling on edge (pop6, pop7)
INFO:siminterface.simulator:Flow 51727 STARTED ARRIVING at node pop5 for processing. Time: 99994.57592756857
INFO:siminterface.simulator:Flow 51727 STARTED PROCESSING at node pop5 for processing. Time: 99994.57592756857
INFO:siminterface.simulator:Flow 51727 started processing at sf c at node pop5. Time: 99994.57592756857
INFO:siminterface.simulator:Flow 51742 STARTED ARRIVING at node pop6 for processing. Time: 99995.05579752533
INFO:siminterface.simulator:Flow 51742 STARTED PROCESSING at node pop6 for processing. Time: 99995.05579752533
INFO:siminterface.simulator:Not enough capacity for flow 51742 at node pop6. Dropping flow.
INFO:siminterface.simulator:Flow 51740 started departing sf a at node pop1. Time 99995.081907921
INFO:siminterface.simulator:Flow 51740 will leave node pop1 towards node pop7. Time 99995.081907921
INFO:siminterface.simulator:Flow 51740 started travelling on edge (pop1, pop10)
INFO:siminterface.simulator:Flow 51733 started departing sf b at node pop4. Time 99995.34277193123
INFO:siminterface.simulator:Flow 51733 will leave node pop4 towards node pop1. Time 99995.34277193123
INFO:siminterface.simulator:Flow 51733 started travelling on edge (pop4, pop6)
INFO:siminterface.simulator:Flow 51739 started departing sf a at node pop8. Time 99995.74084190639
INFO:siminterface.simulator:Flow 51739 will leave node pop8 towards node pop5. Time 99995.74084190639
INFO:siminterface.simulator:Flow 51739 started travelling on edge (pop8, pop5)
INFO:siminterface.simulator:Flow 51740 started travelling on edge (pop10, pop7)
INFO:siminterface.simulator:Flow 51728 started travelling on edge (pop7, pop10)
INFO:siminterface.simulator:Flow 51734 started departing sf b at node pop5. Time 99997.07168337656
INFO:siminterface.simulator:Flow 51734 will leave node pop5 towards node pop3. Time 99997.07168337656
INFO:siminterface.simulator:Flow 51734 started travelling on edge (pop5, pop4)
INFO:siminterface.simulator:Flow 51744 generated. arrived at node pop3 Requesting sfc_1 - flow duration: 1.0ms, flow dr: 1.0. Time: 99998.00095826027
INFO:siminterface.simulator:Flow 51744 will leave node pop3 towards node pop7. Time 99998.00095826027
INFO:siminterface.simulator:Flow 51744 started travelling on edge (pop3, pop6)
INFO:siminterface.simulator:Flow 51734 started travelling on edge (pop4, pop3)
INFO:siminterface.simulator:Flow 51740 STARTED ARRIVING at node pop7 for processing. Time: 99998.081907921
INFO:siminterface.simulator:Flow 51740 STARTED PROCESSING at node pop7 for processing. Time: 99998.081907921
INFO:siminterface.simulator:Not enough capacity for flow 51740 at node pop7. Dropping flow.
INFO:siminterface.simulator:Flow 51743 started travelling on edge (pop8, pop9)
INFO:siminterface.simulator:Flow 51728 started travelling on edge (pop10, pop1)
INFO:siminterface.simulator:Flow 51741 STARTED ARRIVING at node pop5 for processing. Time: 99998.62018291667
INFO:siminterface.simulator:Flow 51741 STARTED PROCESSING at node pop5 for processing. Time: 99998.62018291667
INFO:siminterface.simulator:Flow 51741 started processing at sf a at node pop5. Time: 99998.62018291667
INFO:siminterface.simulator:Flow 51733 started travelling on edge (pop6, pop7)
INFO:siminterface.simulator:Flow 51728 STARTED ARRIVING at node pop1 for processing. Time: 99999.45584663888
INFO:siminterface.simulator:Flow 51728 STARTED PROCESSING at node pop1 for processing. Time: 99999.45584663888
INFO:siminterface.simulator:Flow 51728 started processing at sf c at node pop1. Time: 99999.45584663888
INFO:siminterface.simulator:Flow 51727 started departing sf c at node pop5. Time 99999.57592756857
INFO:siminterface.simulator:Flow 51727 will stay in node pop5. Time: 99999.57592756857.
INFO:siminterface.simulator:Flow 51727 was processed and departed the network from pop5. Time 99999.57592756857
INFO:siminterface.simulator:Flow 51745 generated. arrived at node pop4 Requesting sfc_1 - flow duration: 1.0ms, flow dr: 1.0. Time: 99999.88097000461
INFO:siminterface.simulator:Flow 51745 will leave node pop4 towards node pop1. Time 99999.88097000461
INFO:siminterface.simulator:Flow 51745 started travelling on edge (pop4, pop6)
```

Figure 45: simulation running in the console in INFO level

We can change the level information to Warning, Error, Info or Debug by changing the following parameter on the scripts (example when set in Warning): logging.basicConfig(level=logging.WARNING)

The experiments were ran on Ubuntu Distribution on Windows Kernel , using WSL2 (Windows Subsystem Linux) in order the author to use the machine's CPU, as the CPU and Kernel mapping from the host to a Virtual environment wouldn't work.

The results after running the above scripts are saved at **/usr/local/lib/python3.8/distpackages/results/** in CSV format.

For the visualization of the results, Jupyter Lab was used, in order to have a more direct view: Example for Shortest Path algorithm visualization from the CSV file:

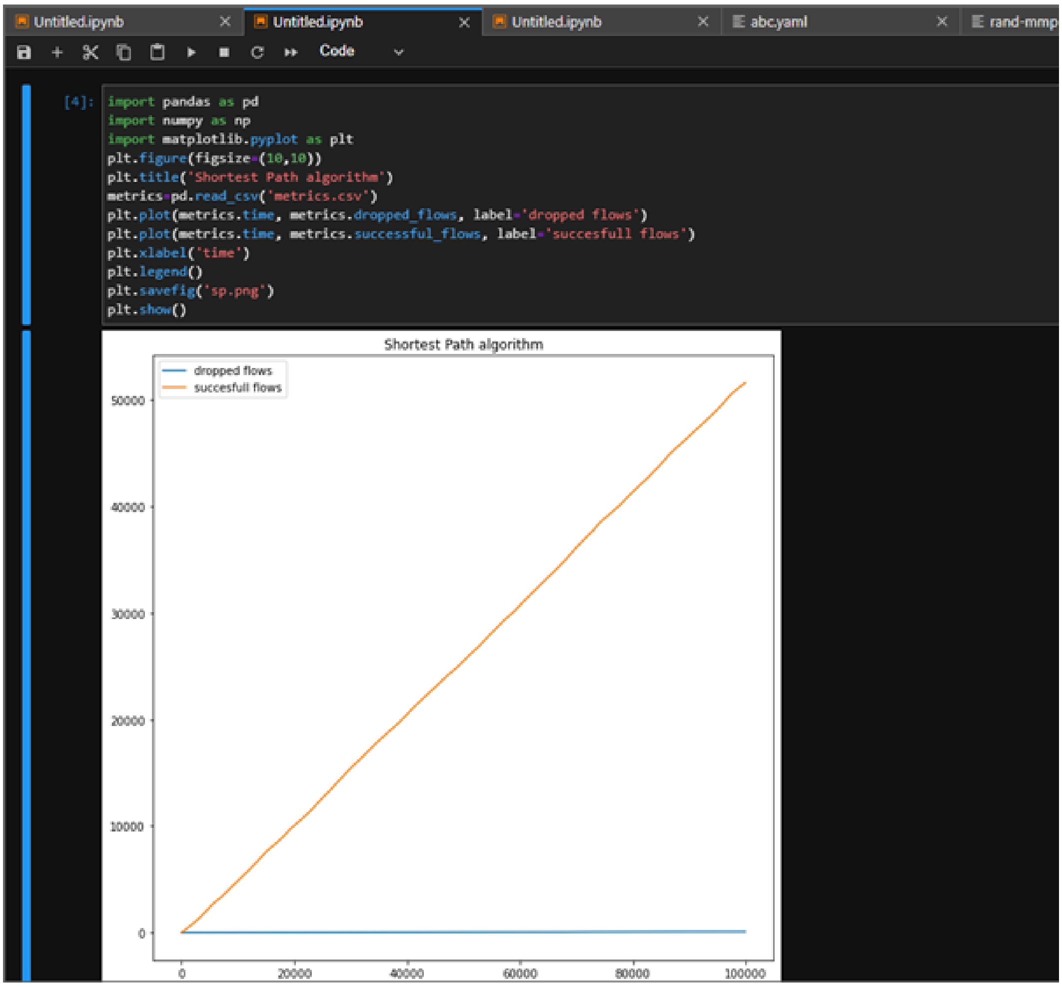


Figure 46: visualization using pandas python library

B´ Author Resume

Christos Kopsacheilis, Msc Digital Communications and Networks, University of Piraeus

- **Personal information**
  Birth date: 1995 | Birth Place: Larissa, Greece

- **Studies**
  2013 , Lyceum Diploma ,1st High school of Giannouli Larissas
  2014-2019: Bachelor of Science (BSc), Mathematics, NKUA
  2019–present: Master of Science (MSc), Digital Communications and Networks, University of Piraeus

- **Work Experience**
  2018- 2020: Cloud Application Support Engineer, Atos
  2020-present: IMS Integration Engineer, Ericsson