

Communication Slice Modeling and Optimization with SARSA Reinforcement Learning

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Abstract

In this document, we present a conceptual model of network slicing, we then formulate analytically some aspects of the model and the optimization problem to address. Next, we propose to use a reinforcement learning SARSA agent to solve the optimization problem and implement a proof of concept prototype highlighting its results.

Index Terms

Network Slicing, Communication Slice, Network Slicing Modeling, Reinforcement Learning, SARSA, Multidomain Slicing, Optimization.



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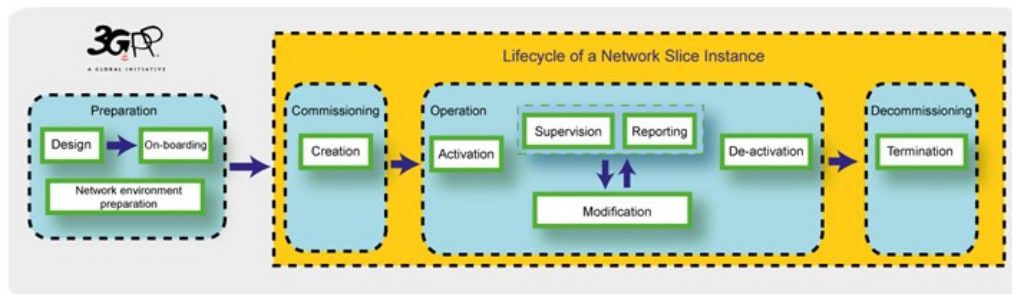
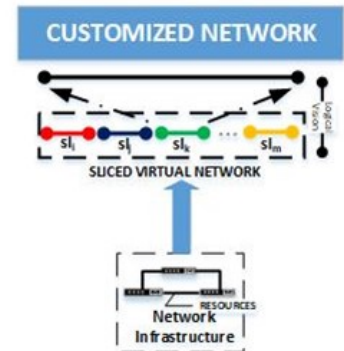
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1 NETWORK SLICING - CONCEPT AND APPLICATION AREAS

Network Slicing Concept and Application Areas

- ◆ Network slicing (NS):
 - Network slicing is a new paradigm that allows the composition and deployment of dynamic virtual networks
- ◆ NS application areas:
 - 5G/6G is the main focus with potential applications for IoT, Internet of Vehicles (IoV), Industry 4.0, and other
- ◆ NS outcome: SLICE or Slice-as-a-Service (SlaaS)
- ◆ On-demand and dynamic virtual networks are created
- ◆ SlaaS composition and deployment is a process with a life cycle:
 - 3GPP NS Life Cycle



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Fig. 1.

— > DISCUSSION OF MAIN POINTS [1]:

Network slicing is a crucial enabler to support the composition and deployment of virtual network infrastructures required by the dynamic behavior of networks like 5G/6G mobile networks, IoT-aware networks, e-health systems, and industry verticals like the internet of vehicles (IoV) and industry 4.0. The communication slices and their allocated communication resources are essential in slicing architectures for resource orchestration and allocation, virtual network function (VNF) deployment, and slice operation functionalities. The communication slices provide the communications capabilities required to support slice operation, SLA guarantees, and QoS/ QoE application requirements. Therefore, this contribution proposes a networking slicing conceptual model to formulate the optimization problem related to the sharing of communication resources among communication slices.

Network slicing is a crucial enabler to support the composition and deployment of virtual network infrastructures required by the dynamic behavior of networks like 5G/6G mobile networks, IoT-aware networks, e-health systems, and industry verticals like the internet of vehicles (IoV) and industry 4.0 [2] [3] [4]. In general, the slicing process results from the need to share resources among existing infrastructures to improve performance, provide cost-efficient solutions, and optimize

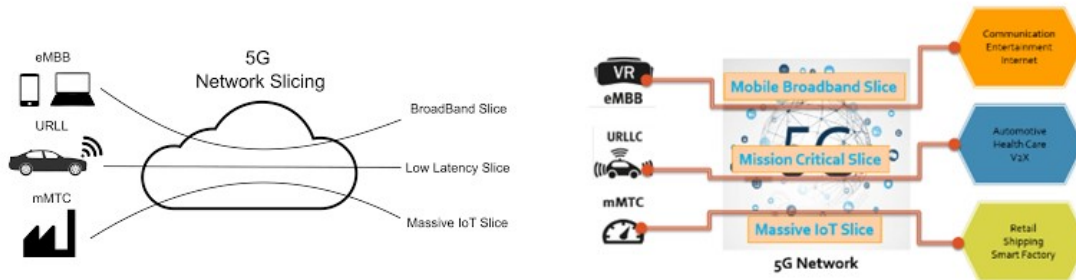
operation [5].

Network slice instance life cycle process such as commissioning, operating, and decommissioning [2] requires appropriate network communication resources.

2 NETWORK SLICING - MARKET AND TRENDS

Network Slicing - Market and Trends

- ◆ NS market – 5G/6G:
 - ISPs, Telecommunication companies, experimental networks, health systems, and other
- ◆ Other NS market business:
 - ISPs, Telecommunication companies and experimental networks
- ◆ Machine learning (ML) is being extensively adopted by NS architectures:
 - 5G, 5G&B, RAN, other
 - IoT and Future IoT
 - Manufacturing: industrial IoT, machine vision, and other



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Fig. 2.

— > DISCUSSION OF MAIN POINTS [1]:

This technology is already used in the context of 5G networks [2] and provided as a service (slice-as-a-Service: SlaaS) by network operators. This allows customs to create their private virtual networks (slices) tailored to their specific application domains and to develop their own business models. Network slicing is expanding its use in other scenarios of telecommunication networks, content provider networks (ISPs), experimental networks, and IoT systems, among others [6].

Among the most common network characteristics that impact the network slicing process, we can mention delay-aware network slicing like in 5G deployments [7], quality of service (QoS) aware network slicing [4], energy-aware network slicing [8], and, in general, application-dependent and multi-domain network slicing [9].

The objective of this discussion is therefore to propose a conceptual model of slice communication and formulate analytically some of its aspects. The model should be able to capture the set of communication resources to support the optimization of the allocation of communication resources to the different slices on top of various underlying technologies (e.g. Elastic Optical Networks - EON [10], MultiProtocol Label Switching - MPLS, others).

3 NETWORK SLICING - ARCHITECTURES

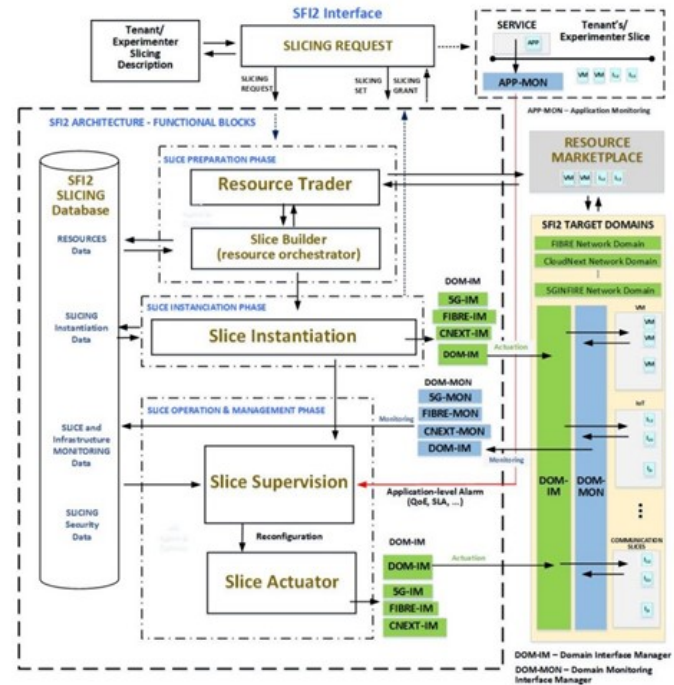
Network Slicing - Architectures

◆ NS architectures:

- Open research issue:
 - ◆ Standardization: 3GPP, IETF, ITU-T, ETSI, ONF.
 - ◆ Research projects: SFI2, NECOS, MATILDA, SELFNET, and other

◆ SFI2 NS architecture:

- Multidomain
- Multitechnology
- Experimental Network integration focus (FIBRE, CloudNext, 5GINFIRE, FUTEBOL, FIWARE, ...)



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Fig. 3. Available at [11]

-- > DISCUSSION OF MAIN POINTS [1]:

There have been a very significant number of state-of-art research projects launched in the area during the last decade such as SFI2 (Slicing Future Internet Infrastructures) [12] [11], NECOS (Novel Enablers for Cloud Slicing) [13], SELFNET [14] and MATILDA [15], standardization initiatives launched by the IETF (Internet Engineering Task Force) [16], 3GPP (3rd Generation Partnership Project) [17], ITU (ITU-T - Telecommunication Standardization) [18], ETSI (European Telecommunications Standards Institute) [19] and ONF (Open Networking Foundation) [20] and published surveys [3] [21] [22] [23] [24]. These different initiatives have focused on different technical aspects, architectures, and slicing strategies, and all require communication slices to operate and manage the provided functionalities.

However, these slicing architectures, projects, and initiatives did only address the conceptual and analytical modeling of the basic structures and functionalities that compose the slicing process in a preliminary way or did only indicate them as future challenges to solve. To the best of our knowledge, the conceptual and analytical modeling of communication slices is a new contribution to the network slicing domain.

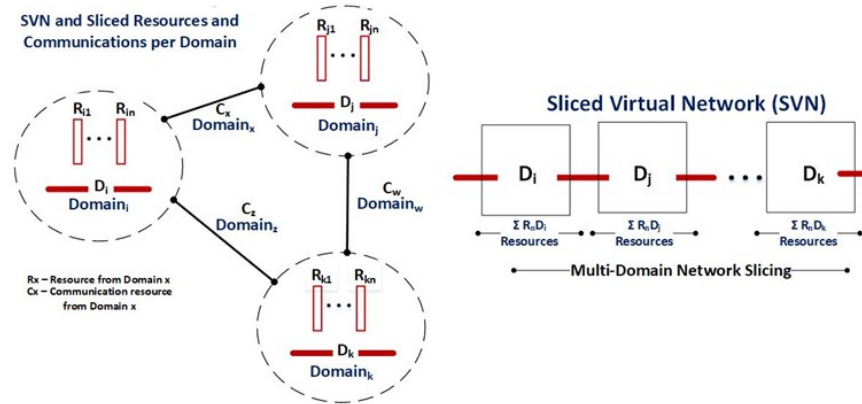
The network slicing architecture functionalities (resource marketplace, resource broker, resource orchestrator, slice instantiation, slice monitoring, and others) are distributed in terms of the domains participating in the SVN deployment and certainly, depend on the proposed architecture and the deployed functional blocks of the network slicing architecture (SELFNET, NECOS, SFI2, MATILDA, other).

4 NETWORK SLICING - THE COMMUNICATION RESOURCE ISSUE

Network Slicing – The Communication Resource Issue



- ◆ What is our focus in terms of NS?
 - ◆ The communication resource issue or Communication Slice
- ◆ Resources, Slice and Sliced Virtual Network (SVN)
 - ◆ Slice as a component of the sliced virtual network



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Fig. 4. Available at [1]

— > DISCUSSION OF MAIN POINTS [1]:

A communication slice¹ represents a set of communication resources that can be used in the slicing process. It holds resources like links, optical slots, virtual private networks (VPNs), and other communication facilities necessary to provide the exchange of information among logical slices, and architectural slicing entities and for supporting the slicing process functionalities.

For the scope of this discussion aiming at the slicing model and deployment understanding, it is essential to conceptualize the vision of a *slice* as a component of the sliced virtual network.

We define a slice as a specific resource, service, function, or set of resources, services, and functions virtualized, shared, and grouped using any software or hardware facility. The slice with its resources, services, and functions physically resides in nodes or another physical or virtual deployment in domains.

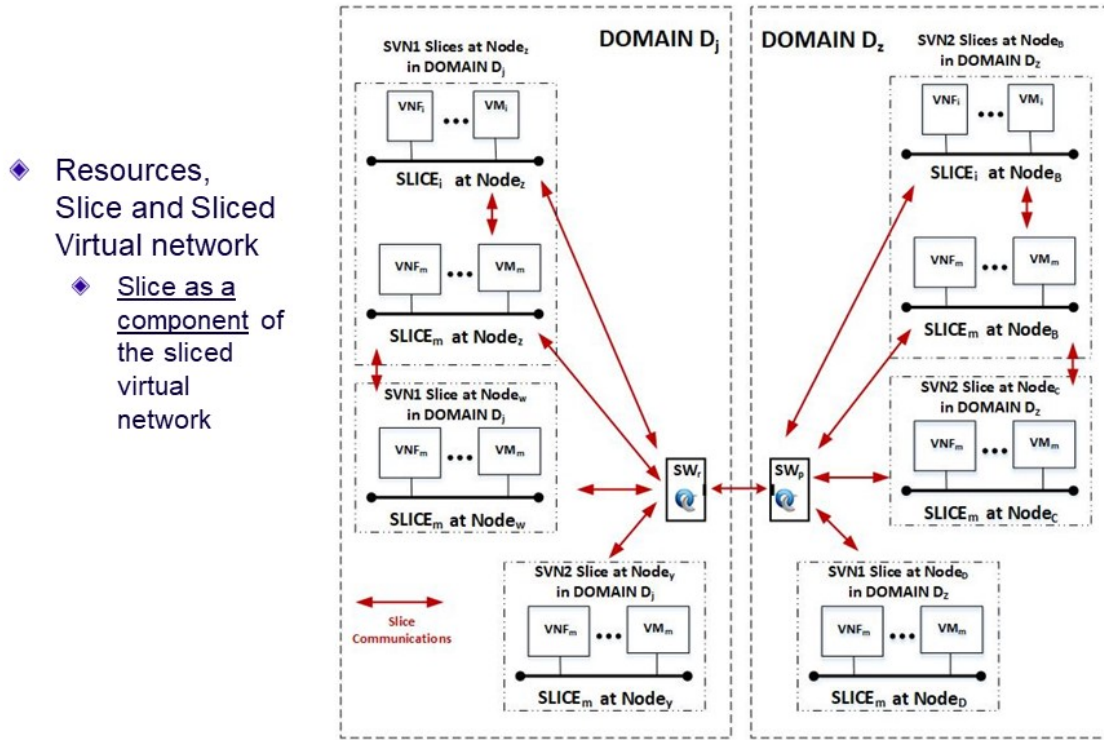
As such, slice resource examples are virtual machines, virtual switches with hosts deployed with OpenFlow, chunks of bandwidth belonging to a physical link, slots of a fiber EON deployment, LSP MPLS connections, shared spectrum in 5G radio access networks (RAN), and others. Slice function and service examples are virtual network functions (VNFs) deployed over a network providing specific services or facilities to the user.

Considering this slice basic concept, an SVN encompasses resources, services, and functions with the necessary communication resources to interconnect them inside domains and between domains.

1. A specialized slice that provides communication services among network slicing entities

5 NETWORK SLICING - THE COMMUNICATION RESOURCE ISSUE

Network Slicing – The Communication Resource Issue



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Fig. 5. Available at [1]

— > DISCUSSION OF MAIN POINTS [1]:

In order to allow the execution of the network slicing process and functionalities in any deployed slicing architecture, it is necessary to allocate communication resources allowing communication among the entities involved in the slicing process. Furthermore, once the SVN is deployed, communication resources are also necessary to support the communication requirements of the applications running (slice operation).

We assume that the slicing process to create a sliced virtual network (SVN) involves single or multiple domains (D_x, \dots, D_z). Each domain is generically configured by a single or a set of nodes (n_i, \dots, n_j) hosting resources and domains that are interconnected by communication resources.

A *communication slice* is then defined as a set of communication resources orchestrated and allocated between slices, nodes, network-slicing entities, and domains. As such, the domain nodes (n_i, \dots, n_j) hosting resources and domains are interconnected by communication slices (C_x, \dots, C_y).

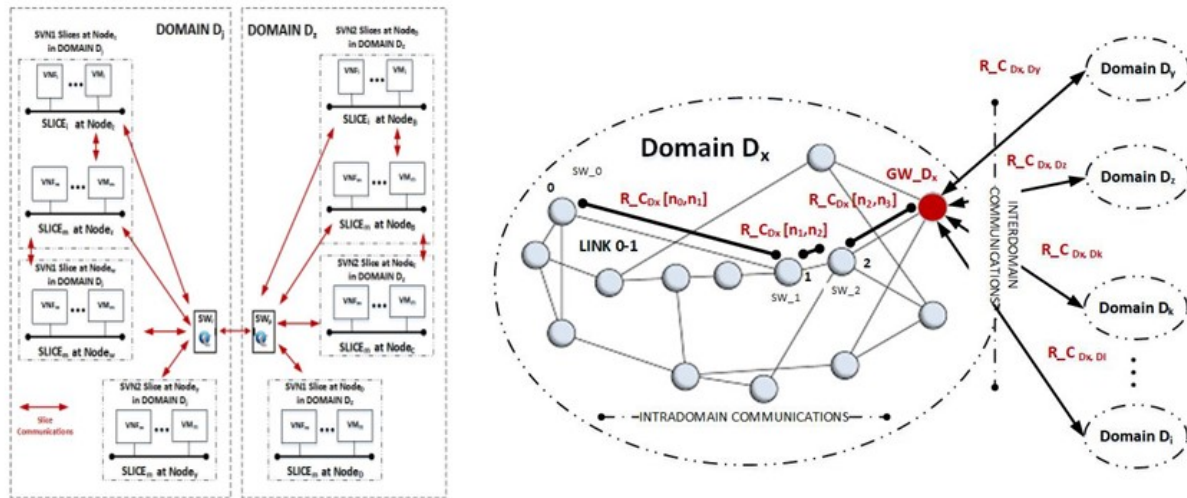
We identify two types of communication slices that are orchestrated and deployed with distinct configurations and characteristics:

- Intradomain communication slices; and
- Interdomain communication slices.

6 NETWORK SLICING - COMMUNICATION SLICE

Network Slicing Communication Slice

- ◆ Communication slices:
 - ◆ Illustration: slices with allocated communication resources
 - ◆ SVN deployment implies in multiple alternatives of using the communication slice



8

Fig. 6. Available at [1]

-- > DISCUSSION OF MAIN POINTS [1]:

In infrastructures composed of network domains, the modeling assumes that a gateway concentrates all communications between different domains.

We focus in this discussion specifically on interdomain communications and how to model it in terms of communication slices.

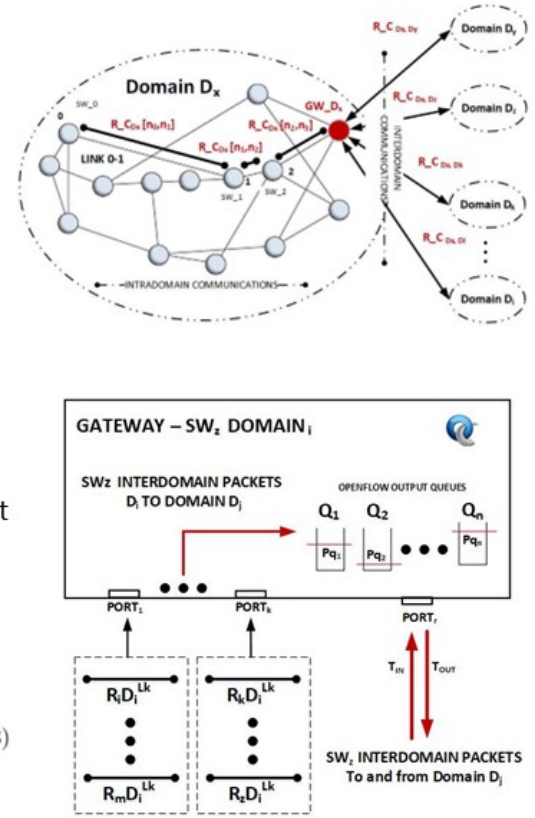
7 COMMUNICATION SLICE - MODELING AND DEPLOYMENT

Communication Slice Modeling and Deployment

- ◆ Conceptual model developed aiming communication slice optimization
- ◆ Summary:
 - ◆ Each network domain is SDN-compatible
 - ◆ Each network domain gateway is an SDN-enabled switch whose programmed behavior is to route packets between domains
 - ◆ The communication slices are characterized by a set of parameters related to interdomain (Eq 3) and intradomain (Eq 4) communications
 - ◆ Our focus will be on Interdomain

$$P_{RC_{D_i, D_j}} = \langle B_{D_i, D_j}, L_{D_i, D_j}, D_{l_{D_i, D_j}} \rangle \quad (3)$$

$$P_{RC_{n_i, n_j}} = \langle B_{n_i, n_j}, L_{n_i, n_j}, D_{l_{n_i, n_j}} \rangle \quad (4)$$



9

Fig. 7. Available at [1]

— > DISCUSSION OF MAIN POINTS [1]:

The objective of a network slicing interdomain communication model is to formally structure and capture the needs in terms of communications for the slicing process. It also allows the identification of parameters leading to the optimization of the resource allocation process.

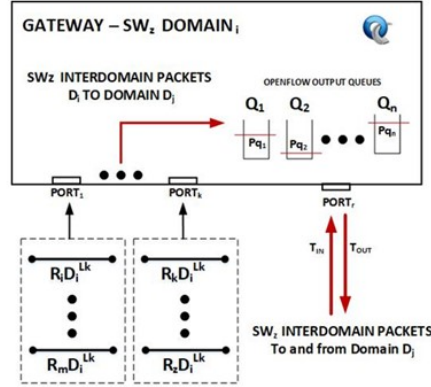
We first introduce the following assumptions in the context of network-slicing interdomain communications that are necessary for our modeling and problem formulation:

- Each network domain is SDN-compatible;
- Each network domain gateway GW_D_i is an SDN-enabled switch whose programmed behavior is to route packets between domains;
- Each network domain implements monitoring mechanisms to collect performance monitoring parameters;
- All intradomain and interdomain links are configurable in terms of allocated resources; and
- All network domains support network resource identification and have capabilities for resource allocation.

8 SVN AND INTERDOMAIN COMMUNICATION SLICE

SVN and InterDomain Communication Slice

- ◆ The interdomain communication slice parameters $P_RC_{D_k, D_j}^{l_i}$ are configured during the commissioning phase according with 3GPP network slicing reference architecture
- ◆ In summary, the interdomain traffic at the gateway is composed by the packets generated (operation and management) by all resources belonging to the domain D_i having as destination the domain D_j



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Fig. 8. Available at [1]

— > DISCUSSION OF MAIN POINTS [1]:

Based on these assumptions, we can now specify an analytical model of multi-domain SVN considering a set of network domains federating together their resources and infrastructures to the slicing process:

$$\aleph = \langle D_i^{l_i}, D_j^{l_j}, D_k^{l_k}, \dots, D_z^{l_z} \rangle \quad (1)$$

Where:

- $RD_i^{l_i}$ is the set of shareable resources provided by D_i and located at site l_i ; and
- $R_i^{D_i^{l_i}}$ is one particular shareable resource.

There are different types of resources at each network infrastructure domain location $D_i^{l_i}$:

- Infrastructure appliances like virtual machines, access points, and IoT devices;
- Computing services like virtual network functions (VNF), storage and computing services; and
- Communications services like physical links, LSPs (MPLS Link Switched Paths), fiber lambdas, and 5G connections.

For the purpose of the SVN model, we distinguish between two types of resources:

- Infrastructure and service resources - $R_IS_{D_i^{l_i}}$; and
- Communications resources - $R_C_{D_i^{l_i}}$.

9 SARSA AGENT OPTIMIZATION

SARSA Agent Optimization



- ◆ The optimization problem to solve here is the sharing of the communication resources between the different slices considering the performance requirement (e.g.: QoS) of each slice
- Target is an efficient communication slice using a SARSA agent
- ◆ The objective of the SARSA agent is to control the queue flushing transmission rates to preserve the performance parameters defined by the manager while sharing unused resource

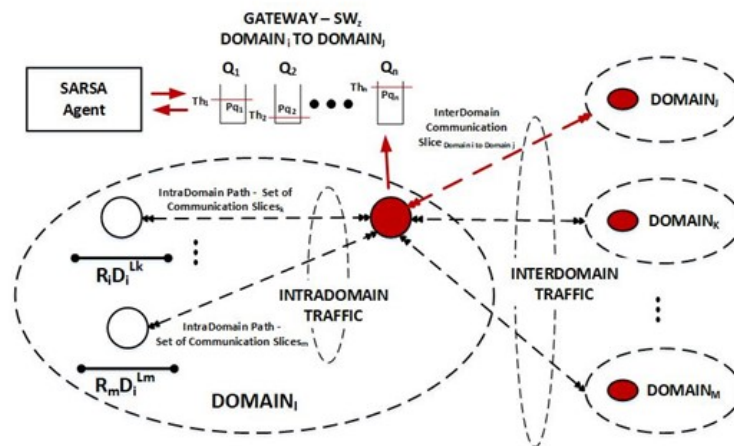


Fig. 9. Available at [1]

-- > **DISCUSSION OF MAIN POINTS [1]:**

The interdomain slice communication parameters $P_{RC_{D_k, D_j}}^{l_i}$ are configured during the slicing commissioning phase, as proposed in the 3GPP network slicing reference architecture and model [25].

An SVN will require resources of distinct domains to be allocated end-to-end:

$$SL_k^{D_i} = \langle R_i^{D_i}, R_j^{D_i}, R_k^{D_i}, \dots, R_z^{D_i} \rangle \quad (2)$$

The communication slice modeling assumes that each domain contributes to a set of different resources that are located in various physical sites (domains).

The model is agnostic to the issue of traffic distinction between packets generated with the slices already instantiated (slice operation) and packets generated by the network slicing management software installed (orchestrator, resource marketplace, monitoring, others).

In summary, the interdomain traffic at the gateway is composed of the packets generated (operation and management) by all resources belonging to the domain D_i having as destination the domain

D_j .

For the interdomain packets at the gateway, the following definitions hold:

- All packets belonging to a set of resources $R_i^{D_i}$ at domain D_i with the same performance parameters constraint use a specific queue Q_n ;
- N switch queues handle the packet generated by the shareable resources at domain D_i ;
- The switch queues have SDN resources control capabilities controlled by SDN Controllers [26] for resource control;
- A priority is assigned to each output queue; and
- Each queue has a threshold level control parameter P_{Q_n} .

The priority and threshold level assigned to the queues are used to support optimization (e.g. optimization controller as shown in the following section).

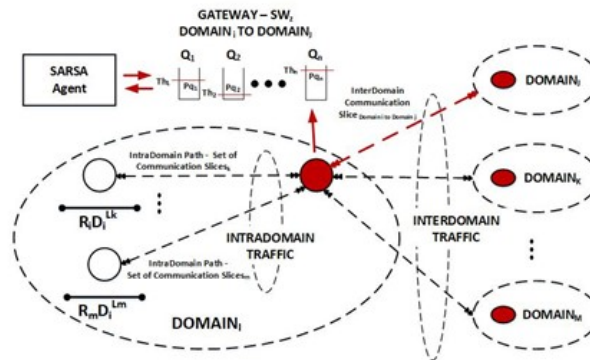
In summary, the model assumes that packets generated from any sliced resource with similar performance constraints are grouped in the same controlled queue in the gateway.

10 SARSA AGENT CONFIGURATION

SARSA Agent Configuration



- ◆ Three queues corresponding to three performance parameters controlled by the agent
- ◆ Each configured queue threshold (Th_i) corresponds to the performance parameter assigned to the queue and served to packets generated by sliced resources with this requirement
- ◆ Each queue Q_i has two states: below threshold (BT) and above threshold (AT)
- ◆ Main SARSA parameters:
 - ◆ Epsilon-greedy policy (ϵ) = 8%
 - ◆ Learning rate (α) = 20%
 - ◆ Discount factor (γ) = 80%
 - ◆ Threshold limit = 50%
 - ◆ Agent actions: bandwidth increased or reduced by 10%
 - ◆ Queue priorities are: p_1, p_2 and p_3 with $p_1 > p_2 > p_3$



13

Fig. 10. Available at [1]

— > DISCUSSION OF MAIN POINTS [1]:

The objective of the SARSA agent is to control the queue flushing transmission rates to preserve the performance parameters defined by the manager while sharing unused resources.

The slice communication queues (Q_i) are configured as follows: i) Three queues corresponding to three performance parameters controlled by the agent; ii) Each configured queue threshold (Th_i) corresponds to the performance parameter assigned to the queue and served to packets generated by sliced resources with this requirement; and iii) Each queue Q_i has two states: below threshold (BT) and above threshold (AT).

The actions defined for the queues in the *AT* state are to increase the transmission rate, reduce the transmission rate, and do nothing. Each executed state/action has a defined reward.

The SARSA agent and communication slice parameters and initial conditions for running are as follows:

- Agent configuration parameters: i) Epsilon-greedy policy $\epsilon = 8\%$; ii) Learning rate $\alpha = 20\%$; and iii) Discount factor $\gamma = 80\%$

- Other parameters are: i) Threshold limit (triggers agent action) = 50%; ii) Agent actions: bandwidth increased or reduced by 10%; iii) the Maximum number of attempts = 500; and iv) Queue priorities are: p_1 , p_2 and p_3 with $p_1 > p_2 > p_3$.

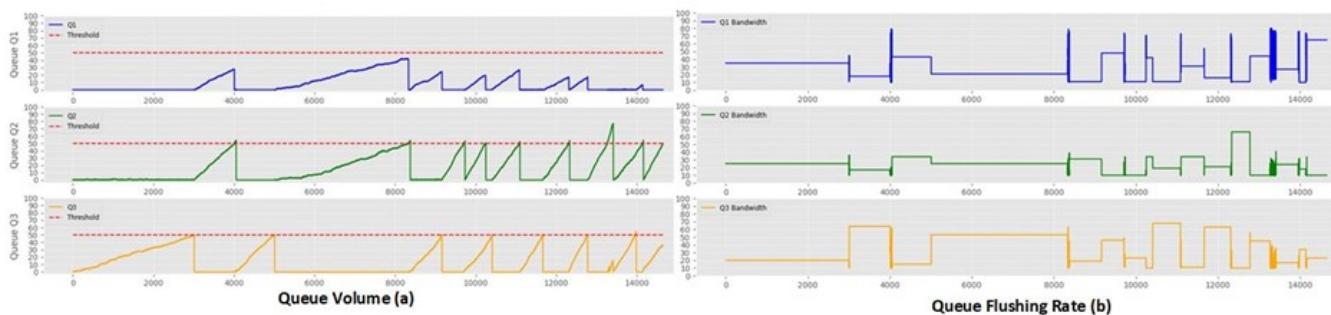
11 PROOF OF CONCEPT - SARSA RESULTS

Communication Slice SARSA Proof of Concept Results

◆ Evaluation scenarios:

- ◆ Scenario 1 - One of the queues is overloaded
- ◆ Scenario 2 - Two queues are overloaded; and
- ◆ Scenario 3 - All queues are overloaded

◆ Test scenario 1:



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Fig. 11. Available at [1]

-- > DISCUSSION OF MAIN POINTS [1]:

The simulation environment was configured on a Linux (Ubuntu 22.04.1 LTS) Intel(R) Core(TM) i5-3470 CPU @ 3.20GHz desktop. Visual Studio Code v.1.73.0 and Python v3.10.6 are used to execute the tests and the statistical analysis.

The dynamics of the overloaded queues are configured as follows: i) First set traffic 30% above the queue's defined limit for 10 minutes; ii) Increase to 50% above its defined limit for additional 10 minutes; iii) Increase to 80% above its defined limit for additional 10 minutes, and iv) Increase to 100% above its defined limit for additional 10 minutes.

Figure 11 illustrates the SARSA agent's behavior for scenario one. Figure 11a plots the state of the queues while they are being saturated with overload traffic of packets. The queue transmission rate (flushing rate) configured by the SARSA agent is illustrated in Figure 11b. We observe that the total available bandwidth for the link is distributed and reconfigured among the queues according to the dynamic need to flush packets from a specific queue and keep queue occupation below the defined threshold.

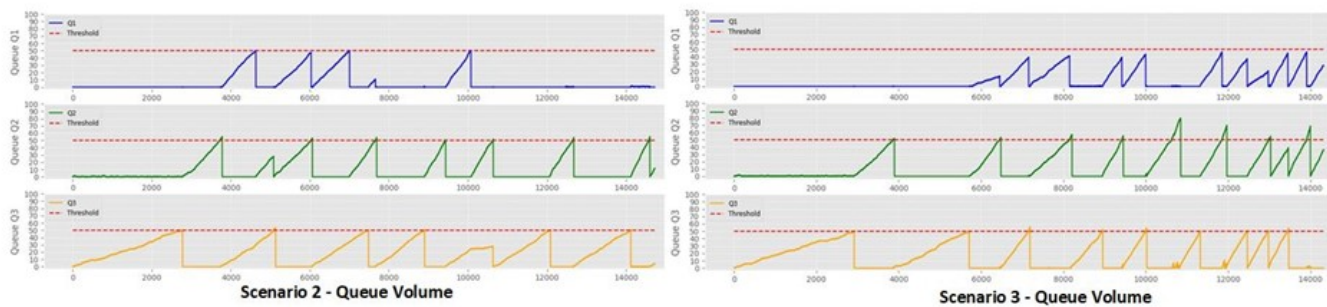
12 PROOF OF CONCEPT - SARSA RESULTS

Communication Slice SARSA Results

◆ Evaluation scenarios:

- ◆ Scenario 1 - One of the queues is overloaded
- ◆ Scenario 2 - Two queues are overloaded; and
- ◆ Scenario 3 - All queues are overloaded

◆ Test scenario 2 and 3



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Fig. 12. Available at [1]

DISCUSSION OF MAIN POINTS [1]:

For scenarios two and three, the behavior of the SARSA agent is illustrated in Figure 12. In scenario two, two queues may overload, and, as observed in scenario one, the SARSA agent reconfigures the queue's transmission rate to keep buffer occupation below the defined threshold. The agent can deal with simultaneous overload for the simulation-defined parameters by keeping queue occupation as required. The behavior of the SARSA agent in scenario 3 is equivalent to its behavior in scenario two.

13 FINAL CONSIDERATIONS

Final Considerations

- ◆ A conceptual model of network slicing is presented to allocate communication resources between slicing processes
- ◆ SARSA agent optimizes the allocation of communication resources for interdomain communication slices
- ◆ Proof of concept of the SARSA agent aims to demonstrate that the SARSA agent contributes to dynamically adjusting and controlling the slice communication parameters between domains
- ◆ Future work includes the leverage of the conceptual model with the integration of intradomain and interdomain models and a new formulation for the distributed optimization problem to solve by a federation of SARSA agents



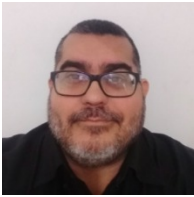
Fig. 13.

DISCUSSION OF MAIN POINTS [1]:

This discussion presents a conceptual model of network slicing and presents an analytical model to allocate communication resources between slicing processes. The conceptual model is along with a SARSA agent that optimizes the allocation of communication resources among slices. The SARSA agent uses the conceptual model to formulate the required communication resources of each slice. A proof of concept implementation of the SARSA agent aims to demonstrate that the SARSA agent contributes to dynamically adjusting and controlling the slice communication parameters between domains. The proposed conceptual model demonstrates the feasibility and ease of handling different types of communication resources for optimizing the communication slice. Future work includes the leverage of the conceptual model with the integration of intradomain and interdomain models and the new formulation of the distributed optimization problem to solve by a federation of SARSA agents.

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