



Model Identification and Control of Priority Queueing in Software Defined Networks

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Abstract

The heterogeneity of modern network infrastructures involves different devices and protocols bringing out several issues in organizing and optimizing network resources, making their coexistence a very challenging engineering problem. In this scenario, Software Defined Network (SDN) architectures decouple control and forwarding functionalities by enabling the network devices to be remotely configurable/programmable in run-time by a controller, and the underlying infrastructure to be abstracted from the application layer and the network services, with the final aim of increasing flexibility and performance. As a direct consequence identifying an accurate model of a network and forwarding devices is crucial in order to apply advanced control techniques such as Model Predictive Control (MPC) to optimize the network performance. An enabling factor in this direction is given by recent results that appropriately combine System Identification and Machine Learning techniques to obtain predictive models using historical data retrieved from a network. This thesis presents a novel methodology to learn, starting from historical data and appropriately combining autoregressive exogenous (ARX) identification with Regression Trees (RT) and Random Forests (RF), an accurate model of the dynamical input-output behavior of a network device that can be directly and efficiently used to optimally and dynamically control the bandwidth of the queues of switch ports, within the SDN paradigm. Both the Mininet network emulator environment and a real dataset obtained from measurements of the network of an Italian internet service provider (Sonicatel S.r.l.) have been used to validate the prediction accuracy of the derived predictive models. The benefits of the proposed dynamic queueing control methodology in terms of Packet Losses reduction and Bandwidth savings (i.e. improvement of the Quality of Service) has been finally demonstrated.

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Introduction

A communication network involves the interconnection of a large number of devices, protocols and applications, as well as application-, service- and user-specific Quality of Service (QoS) and Quality of Experience (QoE) requirements: the problem of optimizing the performance of such a complex distributed system while guaranteeing the desired QoS and QoE specifications is a very challenging engineering problem since the heterogeneity and complexity of such network infrastructures pose a number of challenges in effectively modeling, managing and optimizing network resources (e.g. see [1, 2] and references therein).

Thanks to the recently introduced Software Defined Network (SDN) paradigm [3] the control plane and the data plane are decoupled: this enables the possibility of learning (i.e. identifying) dynamical network models to be used for management and optimization purposes. Indeed, in SDN, network resources are managed by a logically centralized controller that have a global view of the network: this feature provides the capacity of monitoring and collecting, in real-time, data on the network state and configuration as well as packet and flow-granularity information [4]. More in detail, a SDN controller device can configure the forwarding state of each switch by using a standard protocol called OpenFlow (OF) [5]. Thanks to the OF *counter variables* (e.g. flow statistics, port statistics, queue statistics, etc.), the controller can retrieve information (feedback) from the network devices and store/process them for optimization purposes [6]. A SDN controller can supervise many aspects of traffic flow, as segment routing and queue management on switch ports.

Indeed, the most difficult challenge to be addressed in order to apply optimization techniques is to derive a predictive model of the queues of the switch behaviour. To the best of the author knowledge the state of the art in deriving accurate dynamical models of communication networks still lacks of methods that exploit historical network data to learn (identify) a dynamical network model that can be directly used for optimal control (e.g. of segment routing and/or queue management) and is practical from the computational complexity point of view.

The goal of this research is exploiting control theory combined with Machine Learning techniques to compute an accurate model for predicting queues state inside a switch ports,

and use this model to optimally control queues scheduling via bandwidth allocation. In particular, a novel methodology to learn an accurate model of the dynamical input-output behavior of a switch device starting from historical data, that combines ARX identification with Regression Trees (RT) and Random Forests (RF) algorithms [7, 8, 9], has been presented as the main contribution [10]. At first a comparison between the prediction accuracy of the proposed technique with respect to Neural Network (NN) models has been shown. Then in a network emulation environment the proposed novel identification technique (differently from NNs, that provide nonlinear predictive models that are impractical for optimization from the computational complexity viewpoint) has been directly and efficiently used to control the bandwidth of the queues of switch ports with the final aim of reducing packet losses, and thus improving QoS, taking into account the priority of different services. We validate our approach both on real traffic data and on an emulative setup.

The manuscript is organized as follows: in Chapter 1 a survey on related works is provided; a background knowledge about SDN and Machine learning has been introduced in Section 2.1 and in Section 2.2 respectively; in Section 3.1 the network emulation environment has been illustrated; in Section 3.2 the model identification technique and its embedding in a MPC problem formulation solvable via Quadratic Programming (QP) has been described; in Section 3.3 the prediction accuracy and control performance validation using the proposed emulation environment has been provided.

Chapter 1

Related Works

The problems of modeling, managing and optimizing resources in a heterogeneous communication network is a very challenging engineering problem because of its inherent complexity [1, 2, 11, 12].

Numerous studies have been conducted to maximize the performance of the controller and OpenFlow switch of SDN, however, few results and methodologies exist to model and perform optimal control of SDN switches with priority scheduling. When analyzing the literature regarding traffic management in SDN and priority queueing, we can distinguish three main different approaches.

Heuristic approaches, where algorithms to both identify and control traffic within a queue are based on rule-of-thumbs and empirical approaches that do not take into account any particular model: in [13] a heuristic method is proposed to balance the packet load among queues in order to reduce packet losses, which does not aim at providing an optimal solution; in [14] authors provide a scheduling algorithm for handling the incoming data traffic by enqueueing packets into the corresponding queue based on priority and High Priority queue is dequeued first; in [15] the authors define multiple queues with different priority classes, which are used to prioritize VoIP packet based on delay, and the controller decides where to enqueue the packet based on delay and considering 5 different decision thresholds.

Parametric approaches, where the control of queues is based on less heuristics and more objective methods. More precisely, one or more parameters that describe the QoS of an SDN are chosen and optimization is performed based on *static* models characterised by such parameters: both in [16] and [17] the authors consider different approaches to model and control queuing delays with specific network parameters; in [18] QoE is taken into account in the context of VOIP and the decision metric for selecting the best link for establishing a new VoIP call is based on the MOS quality metric, which is a typical measure of the level of a user's satisfaction of the quality of a call. These approaches despite the

fact that are easy to understand and to implement, may not be often suitable to describe and control traffic flows in large and complex networks as they are not based on a *dynamical* network model.

Model-based approach, where a *dynamical* mathematical model of packet flows within a queue is considered, is the one most related to the research conducted in this thesis. In the classical literature of queuing theory, in particular applied to SDN, most of the approaches are based on classic structures for models [19] and many techniques are exploited to estimate the parameters and the state of a queue [20]. In [21], the authors emphasized that switch performance depends on multiple factors such as: flow-table size, packet arrival rate, etc., and they took these key factors into account for the design of their M/Geo/1 system where the arriving packets follow a Poisson distribution and the service times follows a Geometric distribution; in [22], beside describing a comprehensive review of the literature (mostly M/M/k and M/G/k), authors derived a new model for a queueing network, based on Quasi Birth Death (QBD) processes; another approach based on a dynamical model for Model Predictive Control is described in [23], where the authors derive a Discrete Time Markov Jump Linear System to model a queueing network with the aim of defining predictive control policies based on MPC; finally, in [24] the author proposes a new congestion control algorithm based on MPC, called MPAQM, where the queue length is predicted based on the extended TCP/AQM system model and a state estimator. The main drawback of the approach proposed by the authors here is that they linearize and discretize the model of a TCP/AQM interconnection system as illustrated in [25]; Nonlinear MPC can be applied, but the problem is that the resulting optimization problem can be nonconvex and so hard to solve. In such scenarios, linearization is a solution but not always a good solution because of the fact that linearize a model of a complex system not ensure adequate control performance, especially when the system is going to operate far from of the linearization point.

Obviously the most interesting are the Model-based approaches. However, their main drawback is related to the identification of the model. One issue is related to the need of having access to the queue's buffer data to identify the model and, at least with commercial hardware, this is not possible in general. A second issue is that classical models, such as the ones previously discussed, are usually designed to provide best accuracy for one step prediction. When applying MPC one wants to forecast and exploit the value of state variables for multiple steps ahead: using classical approaches this is achieved by using the prediction computed at $k + 1$ to predict the state at $k + 2$, and so on. This approach is not always accurate when a long prediction horizon is considered, since many additional issues arise such as error propagation and increased uncertainty. In such situations, a multiple

output strategy where a model is able to directly predict the state at different future time steps, or one model for each time step as we will propose in this work, can increase the MPC performance. Of course this comes with additional computational complexity, especially when the number of time steps to be forecasted increases: however, as will be shown later on, this is not an issue in our methodology since the future predictions can be computed exploiting the advantages of binary decision trees and parallel computation.

The last and most important issue is that the mathematical models proposed in such literature do not allow to directly exploit MPC methods with, simultaneously, good accuracy and a realistically implementable computational complexity, i.e. using Quadratic Programming (QP) solvers. Tackling such research challenges is the main topic of this thesis. Indeed, to the best of the author's knowledge, the state of the art in deriving accurate dynamical models of communication networks still lacks of methods that exploit historical network data to learn (identify) a dynamical network model that can be directly used for optimal control (e.g. of segment routing and/or queue management) and is practical from the computational complexity point of view [1, 2, 26, 27, 28, 29, 30]. This manuscript provides a novel methodology to fill this gap.

In this scenario, computing technologies such as graphic processing and tensor processing units represent a good opportunity to implement advanced control theoretic (e.g. MPC) and machine learning algorithms (e.g. decision trees, deep neural networks, etc.) in the communication networks [31, 32, 33, 34]. In summary, the real-time programmability of SDN controllers and the availability of massive historical data enable the exploitation of data analysis and optimization techniques for improving networks efficiency and performance.

Other Machine Learning (ML) approaches applied to telecommunication networks has been investigated over the years. A Knowledge Plane (KP) approach [35] has been proposed to enable automation, recommendation and intelligence by applying ML and cognitive techniques. However the KP approach has not been prototyped nor deployed because each node of traditional network systems, such as routers or switches, can only view and act over a small portion of the system. This implies that each node can learn only from a (small) part of the complete system and therefore it is very complex to design control algorithms beyond the local domain [36]. Thanks to SDN the network resources are managed by a logically centralized controller that have a global view of the network [3, 37, 38, 39, 40]. This feature provides the capacity of collecting data on the network state and opens the possibility of improving the characteristics of each network device with ML algorithms.

To apply optimization techniques to derive a predictive model of the switch queues behaviour is a difficult challenge to be addressed [41, 42, 43, 44, 45]. On this line of research,

Cello *et al.* provide in [46] a predictive model for estimating QoS in order to detect the need for a re-routing strategy due to link saturation. However, this framework cannot be used to apply traffic optimization techniques. In [47] an initial effort is conducted to derive a general hybrid systems framework to model the flow of traffic in communication networks. In [48] the authors provide a first formulation and implementation, based on hybrid systems theory, of a mathematical and simulative environment to formally model the effect of router/link failures on the dynamics of TCP and UDP packet flows belonging to different end-user services (i.e. http, ftp, mailing and video streaming). However, even though hybrid systems are very effective in modelling a network of routers, using such framework for implementing traffic optimization is out of question for computational complexity issues. A further research question focuses on designing strategies for periodic updating of network models, in order to maintain good performance despite the evolution of the real system [49].

The potential impact of machine learning in networks is evident from the huge literature on the topic: Patcha and Park [50] have given a detailed description of machine learning techniques in the domain of intrusion detection; Nguyen and Armitage [51] focus on IP traffic classification; Bkassiny *et al.* [52] have surveyed existing machine learning based methods in Cognitive Radio Networks; [53] investigated how machine learning techniques can be applied in wireless sensor networks; Wang *et al.* [54] have presented the state-of-the-art on Artificial Intelligence based techniques applied to evolve heterogeneous networks and discussed future research challenges; Buczak and Guven [55] investigated data mining methods for cyber-security intrusion detection; Klaine *et al.* [56] have surveyed machine learning algorithms for self organizing cellular networks; [57] investigated how to improve network traffic control using machine learning techniques; Hodo *et al.* [58] focus on machine learning based Intrusion Detection System; Zhou *et al.* [59] focus on cognitive radio technologies enforced by machine learning techniques to enhance spectrum utilization and energy efficiency of wireless networks; Chen *et al.* [60] have studied neural networks solutions applied in wireless networks for virtual reality and edge caching; Usama *et al.* [32] have applied unsupervised learning techniques in the general domain of networking. Although machine learning techniques have been widely investigated in the communication scientific community, to the best of our knowledge no existing work focuses on the applications of machine learning and control theory for identifying models of network devices in the domain of Software Defined Network (SDN), with the aim of efficiently apply Model Predictive Control.

Chapter 2

Background Knowledge

This chapter briefly presents the main characteristics of SDN and the main ML algorithms of interest. For a more in-depth knowledge on ML applied to the SDN we refer to [33].

2.1 Software Defined Networks Architecture

The Open Networking Foundation (ONF) [61] is a nonprofit consortium dedicated to the development and standardization of SDN. The SDN paradigm has been defined by ONF as follows: “In the SDN architecture, the control plane and data plane are decoupled, network intelligence and state are logically centralized, and the underlying network infrastructure is abstracted from the applications” [37]. A SDN architecture is composed by three main planes, including data plane, control plane and application plane. The architectural components of each plane and their interactions are shown in Figure 2.1. In the following, we give a brief description of these planes and their interactions.

2.1.1 Data Plane

The data plane, or infrastructure plane, is the lowest layer in SDN architecture. This plane is composed by physical switches, virtual switches and others forwarding devices. Virtual switches are software-based switches, which can run on common operating systems. Open vSwitch [62], Indigo [63] and Pantou [64] are three implementations of virtual switches. Physical switches are hardware-based switches. They can be implemented on open network hardware (e.g., NetFPGA [65]) or implemented on networking hardware vendors’ merchant switches. Many networking hardware vendors such as HP, NEC, Huawei, Juniper and Cisco, have supported SDN protocols. Virtual switches support complete features of SDN protocols, while physical switches lack the flexibility and feature completeness. However, physical switches have a higher flow forwarding rate than virtual switches. SwitchBlade

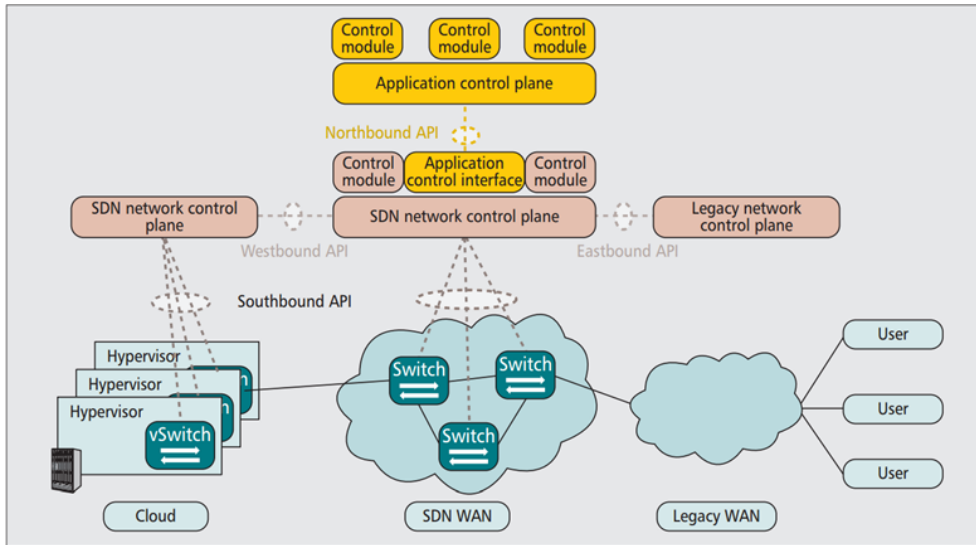


Figure 2.1: The high-level SDN architecture proposed by ONF.

[66] and ServerSwitch [67] are two NetFPGA-based physical switches. These switches in data plane are responsible for forwarding, dropping and modifying packets based on instructions received from the Control Plane (CP) through Southbound Interfaces (SBIs).

2.1.2 Control Plane

The control plane is the “brain” of SDN systems, which can define network resources, dynamically choose forwarding rules and make network administration flexible and agile. The controller is responsible of many relevant tasks like:

- the communication between forwarding devices and applications;
- it exposes and abstracts network state information of the data plane to the application plane;
- it translates the requirements from applications into custom policies and distributes them to forwarding devices;
- provides essential functionalities that most of network applications need, such as shortest path routing, network topology storage, device configuration and state information notifications etc.

There are many controller architectures, such as Ryu [68], OpenDayLight, [69] NOX [70], POX [71], Floodlight [72] and Beacon [73]. Three communication interfaces allow the controllers to interact: southbound, northbound (NBI) and eastbound/westbound interfaces.

The SBIs are defined between the control plane and the data plane. They allow forwarding devices to exchange network state information and control policies with the CP and provide functions such as statistics reports, forwarding operations, programmatic control of all device-capability advertisements and event notifications. OpenFlow [5] promoted by ONF is the first and the most popular open standard SBI. There exist other less popular proposals such as OVSDB [74], Protocol-Oblivious Forwarding (POF) [75] and OpenState [76]. With NBIs, automation, innovation and management of SDN networks has been facilitated thanks to the fact that applications can exploit the abstract network views provided by the CP. The ONF is trying to define the standard NBIs and a common information model. The eastbound/westbound interfaces are used in the multi-controller SDN networks. Due to the vast amount of data flows in such networks and the limited processing capacity of one controller, large-scale networks are always partitioned into several domains where each domain has its own controller. The eastbound/westbound interfaces are responsible for the communication among multiple controllers. This communication is necessary to exchange information in order to provide a global network view to the upper-layer applications. Onix [77] and HyperFlow [78] are two distributed control architectures. Because their eastbound/westbound interfaces are private, they cannot communicate with each other. To enable the communication between different types of SDN controllers, SDNi [79], East-West Bridge [80] and Communication Interface for Distributed Control plane (CIDC) [81] have been proposed as eastbound/westbound interfaces to exchange network information. However, the eastbound/westbound interfaces have not yet been standardized.

2.1.3 Application Plane

The highest layer in the SDN architecture is the application plane. These applications can provide new services and perform business management, optimization and can obtain the required network state information through controllers' NBIs. Based on the received information and other requirements, the applications can apply some control logic to change network behaviors. The SDN-based applications have attracted a lot of attention from academia. Mendiola et al. [82] have discussed the impact of SDN on Traffic Engineering (TE) and surveyed the SDN-based TE solutions. Security in SDN has been surveyed in [83, 84, 85, 86, 87, 88]. Especially, Yan et al. [87] have researched on Distributed Denial of Service (DDoS) attacks in SDN-based cloud computing systems, and discussed future research challenges. Fault management in SDN has been surveyed in [89], which gives an identification and classification of the main fault management issues, and does valuable surveys and discussions about efforts that address those issues. Guck et al. [90] have studied the centralized QoS routing mechanisms in SDN, and introduced a novel Four-Dimensional

(4D) evaluation framework. SDN has been deployed in many networks, such as transport networks [91], optical networks [92], wireless networks [93, 38], Internet of Things (IoT) [94], edge computing [95], Wide Area Networks (WAN) [96], cloud computing [97], Network Function Virtualization (NFV) [98, 99].

For more details on SDN, please refer to [100, 101, 102, 103, 104, 105, 106, 107].

To understand the SDN architecture, it is important to recall its basic operation. Figure 2.2 shows the working procedure of the OpenFlow-based SDN network [6]. Each OpenFlow switch has a flow table and uses the OpenFlow protocol to communicate with the SDN controller. The messages transmitted between the OpenFlow-based switches and the software-based controller are standardized by the OpenFlow protocol [73]. The OpenFlow controller can manage the traffic forwarding by modifying flow entries in switches flow tables. The flow table in the OpenFlow switch is comprised of flow entries to determine the processing actions of different packets on the data plane. When an OpenFlow switch receives a packet on the data plane, the packet header fields will be extracted and matched

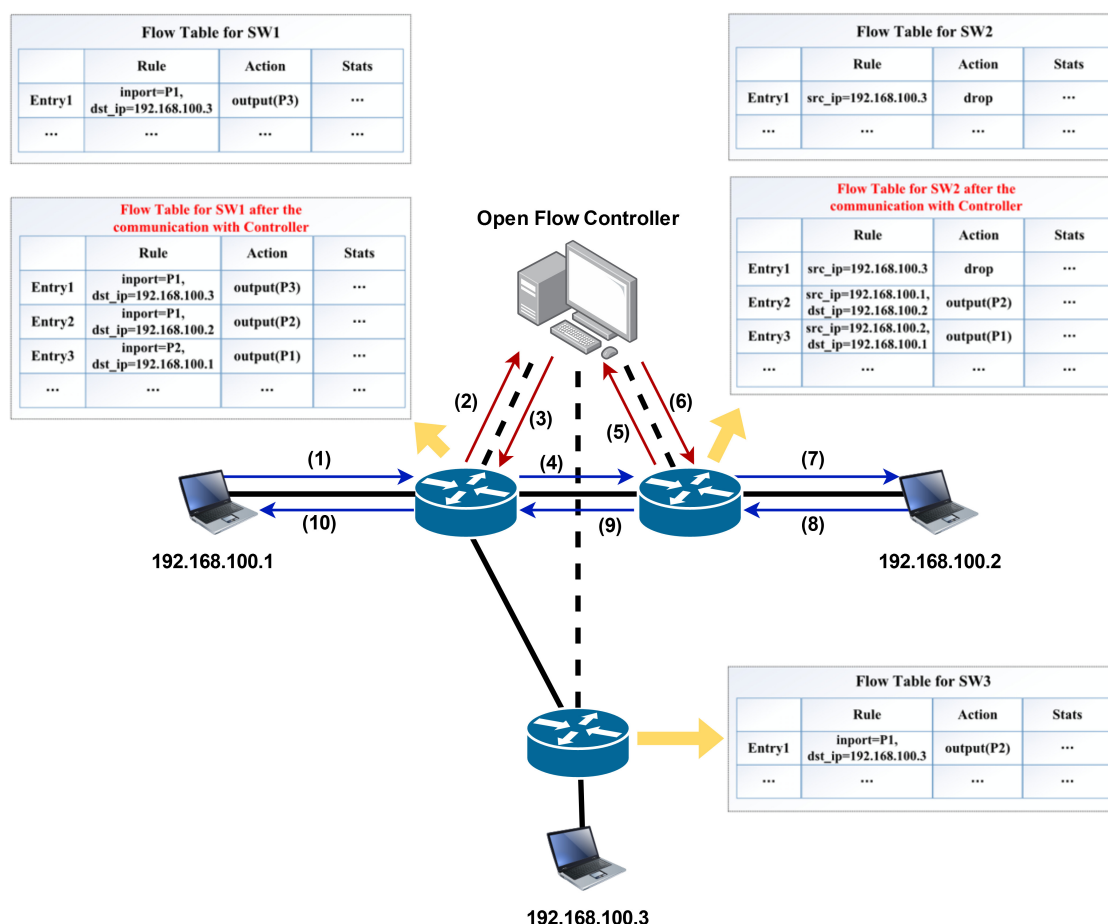


Figure 2.2: Example of OpenFlow-based SDN network.

against flow entries. If a matching entry is found, the switch will process the packet locally according to the actions in matched flow entry. Otherwise, the switch will forward an OpenFlow PacketIn message to the controller (arrows 2 and 5). The packet header (or the whole packet, optionally) is included in the OpenFlow PacketIn message. Then, the controller will send OpenFlow FlowMod messages to manage the switch's flow table by adding flow entries (arrows 3 and 6), which can be used to process subsequent packets of the flow. For example, by adding two flow entries (i.e., Entry2 and Entry3) at SW1 and SW2, the communications between 192.168.100.1 and 192.168.100.2 are allowed. However, packets from 192.168.100.3 to 192.168.100.2 are denied at SW2 due to security policies.

2.2 Overview Of Machine Learning Algorithms

Machine learning is evolved from a collection of powerful techniques in AI areas. These methods start from training data to learn useful structural patterns and models. A machine learning approach consists of two main phases: the training phase and the decision making phase. In the training phase, after a data mining period that creates a training dataset, machine learning methods are applied to learn a system model. In the decision making phase, the trained model is used to estimate the output corresponding to each new input. Machine learning algorithms can be distinguished into four main categories: supervised, unsupervised, semi-supervised and reinforcement learning. Each algorithm in Figure 2.3 is briefly explained with some examples. For a more insightful discussion on machine learning theory, please refer to [108, 109, 110].

2.2.1 Supervised Learning

Supervised learning is a kind of labelling learning technique. Supervised learning algorithms are given a labeled training dataset (i.e., inputs and known outputs) to build the system model representing the learned relation between the input and output. After training, when a new input is fed into the system, the trained model can be used to get the expected output [111, 112]. In the following, an exhaustive representation of supervised learning algorithms is provided:

1) *k-Nearest Neighbor* (k-NN): In k-NN the classification of a data sample is determined based on the k nearest neighbors of that unclassified sample. The process of the k-NN algorithm is very simple: if the most of the k nearest neighbors belong to a certain class, the unclassified sample will be classified into that class. The higher the value of k is, the less effect the noise will have on the classification. Since the

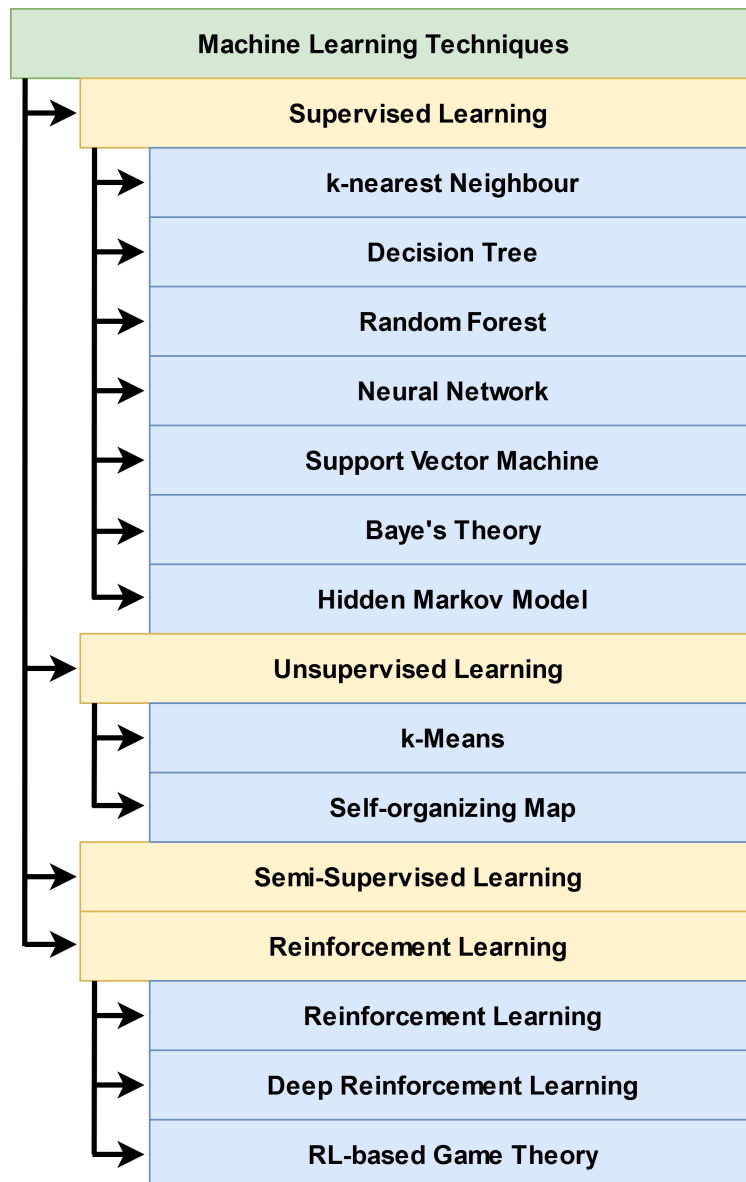


Figure 2.3: Common machine learning algorithms.

distance is the main metric of the k-NN algorithm, several functions can be applied to define the distance between the unlabeled sample and its neighbors, such as Chebyshev, City-block, Euclidean and Euclidean squared [113].

2) *Regression Tree*: The RT performs classification through a learning tree. In the tree, each node represents a data feature, all branches represent the conjunctions of features that lead to classifications, and each leaf node is a class label. The unlabeled sample can be classified by comparing its feature values with the nodes of the RT [114]. The RT has many advantages, such as intuitive knowledge expression, simple

implementation and high classification accuracy. ID3 [115], C4.5 [116] and CART [117] are three widely-used decision tree algorithms. The biggest difference among them is the splitting criteria which are used to build decision trees.

3) *Random Forest*: A RF [118] consists of many RT. To mitigate over-fitting of RT methods and improve accuracy, the random forest method construct each RT by randomly choosing a subset of the features space . The steps to classify a new data sample by using random forest methods are:

- a) Put the data sample in each tree in the forest;
- (b) Each tree gives a classification result (vote);
- (c) The data sample will be classified into the class which has more votes.

4) *Neural Network (NN)*: A neural network is a computing system composed by a large number of simple processing units, which operate in parallel to learn experiential knowledge from historical data [119]. Each neuron performs highly complex, nonlinear and parallel computations. In a NN, its nodes are the equivalent components of the neurons in the human brain. These nodes use activation functions to perform nonlinear computations. The most frequently used activation functions are the sigmoid and the hyperbolic tangent functions. Simulating the way neurons are connected in the human brain, the nodes in a NN are connected to each other by variable link weights. A NN has many layers. The first layer is the input layer, the last layer is the output layer and layers between them are the hidden layers. The output of each layer is the input of the next layer and the output of the last layer is the result. By changing the number of hidden layers and the number of nodes in each layer, complex models can be trained to improve the performance of NNs. NNs are widely used in many applications, such as pattern recognition. In figure 2.4 the most basic NN with three layers has been shown. An input has m features (i.e., X_1, X_2, \dots, X_m) and the input can be assigned to n possible classes (i.e., Y_1, Y_2, \dots, Y_n). Also, W_{ij}^l denotes the variable link weight between the i th neuron of layer l and the j th neuron of layer $l + 1$, and ak^l denotes the activation function of the k th neuron in layer l . There are many types of neural networks, which can be divided in supervised or unsupervised main group [120]. In the following, we will give a brief description of supervised neural networks.

- a) *Random NN*: The random NN can be represented as an interconnected network of neurons that exchange spiking signals. The main difference between

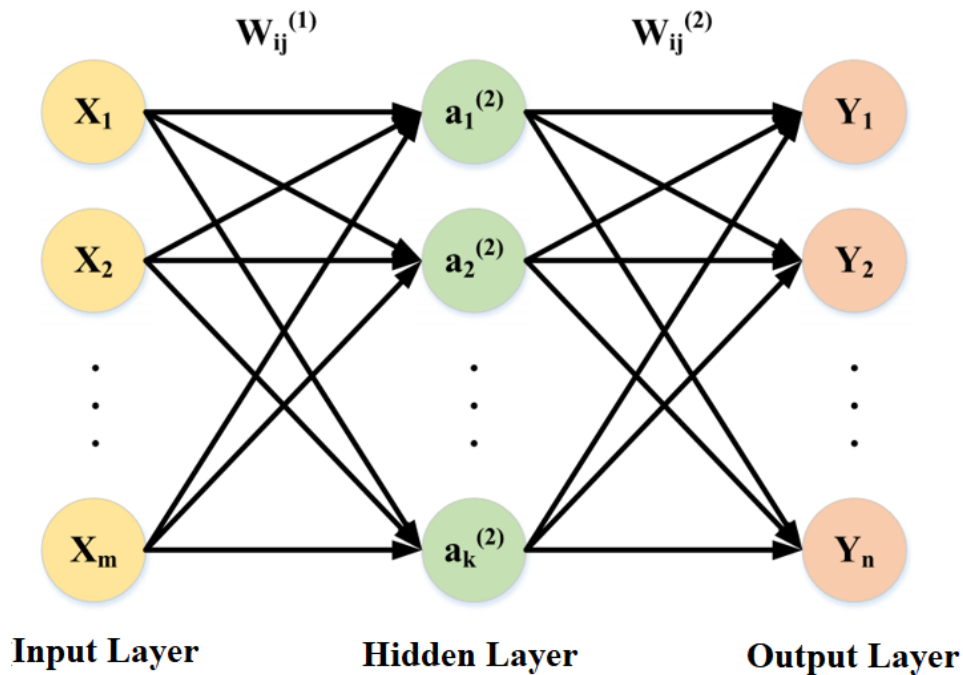


Figure 2.4: A basic neural network with three layers: an input layer, a hidden layer and an output layer.

random NN and other neural networks is that neurons in random NN exchange spiking signals probabilistically. In random NN, the internal excitatory state of each neuron is represented by an integer called “potential”. The potential value of each neuron rises when it receives an excitatory spiking signal and drops when it receives an inhibitory spiking signal. Neurons whose potential values are strictly positive are allowed to send out excitatory or inhibitory spiking signals to other neurons according to specific neuron-dependent spiking rates. When a neuron sends out a spiking signal, its potential value drops one. The random NN has been used in classification and pattern recognition [121].

b) Deep NN: Neural networks with a single hidden layer are generally referred to as shallow NNs. In contrast, neural networks with multiple hidden layers between the input layer and the output layer are called deep NNs [122, 123]. To process high-dimensional data and to learn increasingly complex models, deep NNs with more hidden layers and neurons are needed. However, deep NNs increase the training difficulties and require more computing resources. In recent years, the development of hardware data processing capabilities and the evolved activation functions make it possible to train deep NNs [124]. In deep NNs, each layer’s neurons train a feature representation based on the previous layer’s

output, which is known as feature hierarchy. The feature hierarchy makes deep NNs capable of handling large high-dimensional datasets. Due to the multiple-level feature representation learning, compared to other machine learning techniques, deep NNs generally provide much better performance [124].

c) Convolutional NN: Convolutional NN and recurrent NN are two major types of deep NNs. Convolutional NN [125, 126] is a feed-forward neural network. Local sparse connections among successive layers, weight sharing and pooling are three basic ideas of convolutional NN. Weight sharing means that weight parameters of all neurons in the same convolution kernel are same. Local sparse connections and weight sharing can reduce the number of training parameters. Pooling can be used to reduce the feature size while maintaining the invariance of features. The three basic ideas reduce the training difficulties of convolutional NNs greatly.

d) Recurrent NN: In feed-forward neural networks, the information is transmitted directionally from the input layer to the output layer. However, recurrent NN is a stateful network, which can use internal state (memory) to handle sequential data. Unlike a traditional deep NN, which uses different parameters at each layer, the recurrent NN shares the same parameters across all time steps. This means that at each time step, the recurrent NN performs the same task, just with different inputs. In this way, the total number of parameters needed to be trained is reduced greatly. Long Short-Term Memory (LSTM) [127] is the most commonly-used type of recurrent NNs, which has a good ability to capture long-term dependencies. LSTM uses three gates (i.e., an input gate, an output gate and a forget gate) to compute the hidden state.

5) Support Vector Machine (SVM): SVM is invented by Vapnik and others [128], which has been widely used in classification and pattern recognition. The basic idea of SVM is to map the input vectors into a high-dimensional feature space. This mapping is achieved by applying different kernel functions, such as linear, polynomial and Radial Based Function (RBF). Kernel function selection is an important task in SVM, which has effect on the classification accuracy. The selection of kernel function depends on the training dataset. The linear kernel function works well if the dataset is linearly separable. If the dataset is not linearly separable, polynomial and RBF are two commonly-used kernel functions. In general, the RBF-based SVM classifier has a relatively better performance than the other two kernel functions. The objective of SVM is to find a separating hyperplane in the feature space to maximize

the margin between different classes. The margin is the distance between the hyperplane and the closest data points of each class. The corresponding closest data points are defined as support vectors.

6) *Bayes' Theory*: Bayes' theory uses the conditional probability to calculate the probability of an event occurring given the prior knowledge of conditions that might be related to the event. The Bayes' theory is defined mathematically as the following equation:

$$P(H|E) = \frac{P(E|H)P(H)}{P(E)}$$

where E is a new evidence, H is a hypothesis, $P(H|E)$ is the posterior probability that the hypothesis H holds given the new evidence E , $P(E|H)$ is the posterior probability that of evidence E conditioned on the hypothesis H , $P(H)$ is the prior probability of hypothesis H , independent of evidence E , and $P(E)$ is the probability of evidence E . In a classification problem, the Bayes' theory learns a probability model by using the training dataset. The evidence E is a data sample, and the hypothesis H is the class to assign for the data sample. The posterior probability $P(H|E)$ represents the probability of a data sample belonging to a class. In order to calculate the posterior probability $P(H|E)$, $P(H)$, $P(E)$ and $P(E|H)$ need to be calculated first based on the training dataset using the probability and statistics theories, which is the learning process of the probability model. When classifying a new input data sample, the probability model can be used to calculate multiple posterior probabilities for different classes. The data sample will be classified into the class with the highest posterior probability $P(H|E)$. The advantage of Bayes' theory is that it requires a relatively small number of training samples dataset to learn the probability model [129]. However, there is an important independence assumption when using the Bayes' theory. To facilitate the calculation of $P(E|H)$, the features of data samples in the training dataset are assumed to be independent of each other [130].

7) *Hidden Markov Models (HMM)*: HMM is one kind of Markov models. Markov models are widely used in randomly dynamic environments which obey the memoryless property. The memoryless property of Markov models means that the conditional probability distribution of future states only relates to the value of the current state and is independent of all previous states [131, 132]. There are other Markov models, such as Markov Chains (MC). The main difference between HMM and other models is that HMM is often applied in environments where system states are partially visible or not visible at all.

2.2.2 Unsupervised Learning

In contrast to supervised learning, an unsupervised learning algorithm is given a set of inputs without labels, thus there is no output. An unsupervised learning algorithm aims to find patterns, structures, or knowledge in unlabeled data by clustering sample data into different groups according to the similarity between them. The unsupervised learning techniques are widely used in clustering and data aggregation. In the following, we will give a representation of widely-used unsupervised learning algorithms.

1) *k-Means*: The k-means algorithm is used to recognize a set of unlabeled data into different clusters. To implement the kmeans algorithm, only two parameters are needed: the initial dataset and the desired number of clusters. If the desired number of clusters is k, the steps to resolve node clustering problem by using k-means algorithms are:

- a) initialize k cluster centroids by randomly choosing k nodes;
- b) use a distance function to label each node with the closest centroid;
- c) assign new centroids according to the current node memberships;
- d) stop the algorithm if the convergence condition is valid, otherwise go back to step b).

2) *Self-Organizing Map (SOM)*: SOM, also known as SelfOrganizing Feature Map (SOFM) [133], is one of the most popular unsupervised neural network models. SOM is often applied to perform dimensionality reduction and data clustering. In general, SOM has two layers, an input layer and a map layer. When SOM is used to perform data clustering, the number of neurons in the map layer is equal to the desired number of clusters. Each neuron has a weight vector. The steps to resolve data clustering problem by using SOM algorithm are:

- a) initialize the weight vector of each neuron in the map layer;
- (b) choose a data sample from the training dataset;
- (c) use a distance function to calculate the similarity between the input data sample and all weight vectors. The neuron whose weight vector has the highest similarity is called the Best Matching Unit (BMU). The SOM algorithm is based on competitive learning;
- (d) The neighborhood of the BMU is calculated;

- (e) The weight vectors of the neurons in the BMU's neighborhood are adjusted towards the input data sample;
- (f) Stop the algorithm if the convergence condition is valid, otherwise go back to step (b).

2.2.3 Semi-Supervised Learning

Semi-supervised learning is a type of learning which uses both labeled and unlabeled data. Semi-supervised learning is useful due the fact that in many real-world applications, the acquisition of labeled data is expensive and difficult while acquiring a large amount of unlabeled data is relatively easy and cheap. Moreover effective use of unlabeled data during the training process actually tends to improve the performance of the trained model. In order to make the best use of unlabeled data, assumptions have to be hold in semisupervised learning, such as smoothness assumption, cluster assumption, low-density separation assumption, and manifold assumption. Pseudo Labeling [134] is a simple and efficient semi-supervised learning technique. The main idea of Pseudo Labeling is simple. Firstly, use the labeled data to train a model. Then, use the trained model to predict pseudo labels of the unlabeled data. Finally, combine the labeled data and the newly pseudo-labeled data to train the model again. There are other semi-supervised learning methods, such as Expectation Maximization (EM), co-training, transductive SVM and graph-based methods. Different methods rely on different assumptions. For example, EM builds on cluster assumption, transductive SVM builds on low-density separation assumption, while graph-based methods build on the manifold assumption.

2.2.4 Reinforcement Learning

Supervised learning algorithms are generally applied to conduct classification and regression tasks, while unsupervised and reinforcement learning algorithms are applied to conduct clustering and decision-making tasks respectively.

1) *Reinforcement Learning (RL)*: RL [135, 136] involves an agent, a state space S and an action space A . The agent is a learning entity which interacts with its environment to learn the best action to maximize its long-term reward. The long-term reward is a cumulative discounted reward and relates to both the immediate reward and future rewards. When applying RL to SDN, the controller generally works as an agent and the network is the environment. The controller monitors the network status and learns to make decisions to control data forwarding. Specifically, at each time step

t , the agent monitors a state s_t and chooses an action a_t from the action space A , receives an immediate reward r_t which indicates how good or bad the action is, and transitions to the next state s_{t+1} . The objective of the agent is to learn the optimal behavior policy π which is a direct map from the state space S to the action space A ($\pi : S \rightarrow A$) to maximize the expected long-term reward. From the behavior policy π , the agent can determine the best corresponding action given a particular state. In RL, value function is used to calculate the long-term reward of an action given a state. The most well-known value function is Q-function, which is used by Q-learning to learn a table storing all state-action pairs and their long-term rewards.

2) *Deep Reinforcement Learning (DRL)*: The main advantage of RL is that it works well without prior knowledge of an exact mathematical model of the environment. However, the traditional RL approach has some shortcomings, such as low convergence rate to the optimal behavior policy π and its inability to solve problems with high-dimensional state space and action space. These shortcomings can be addressed by DRL. The key idea of DRL is to approximate the value function by leveraging the powerful function approximation property of deep NNs. After training the deep NNs, given a state-action pair as input, DRL is able to estimate the long-term reward. The estimation result can guide the agent to choose the best action.

3) *RL-Based Game Theory*: Game theory is a mathematical tool that focuses on strategic interactions among rational decision-makers. A game generally involves a set of players, a set of strategies and a set of utility functions. Players are decision-makers. Utility functions are used by players to select optimal strategies. In cooperative games, players cooperate and form multiple coalitions. Players choose strategies that maximize the utility of their coalitions. In non-cooperative games, players compete against each other and choose strategies individually to maximize their own utility. In the network field, it is often assumed that nodes are selfish. In non-cooperative games, players do not communicate with each other, and at the beginning of each play round, players do not have any information about the strategies selected by the other players. At the end of each play round, all players broadcast their selected strategies, which are the only external information. However, each player's utility can be affected by the other players' strategies. In this case, adaptive learning methods should be used to predict the strategies of the other players, based on which each player chooses its optimal strategy. RL is a widely-used adaptive learning method,

which can help players select their optimal strategies by learning from historical information such as network status, the other players' strategies and the corresponding utility. Thus, RL-based game theory is an effective decision-making technique.

Chapter 3

RT- and RF-based models of SDN switched for Priority Queueing

This chapter first describes a SDN Mininet emulation environment that we use to generate traffic packets (starting from real data patterns) and to retrieve network (feedback) information via the SDN controller, thanks to the OF protocol. Then we shown how to use data collected from such environment to create a predictive model of the switch priority queueing scheuling.

3.1 Mininet network emulation environment and control problem

The Mininet environment [137] has been used to emulate a SDN network to validate our methodology in terms of prediction accuracy and control performance. This software runs a collection of virtual network elements (i.e. end-hosts, switches, routers, and links) on a single Linux kernel using lightweight virtualization. To generate traffic we used the D-ITG generator [138, 139, 140].

For the purposes of this work, various network configurations were tested. Since similar results has been obtained on all configurations, it is possible to consider the generic case as the architecture in Figure 3.1, which aims to represent a portion of a larger network where a bottleneck occurs. More precisely, we consider a switch s_0 with one input port and one output port, and a remote controller [62, 68] that dynamically manages the configuration of the queues of s_0 . The input of s_0 is fed with an instance of D-ITG generating stochastic traffic, whose mean value follows the pattern of a real data set (where packets are differentiated by their ToS - Type of Service - priority index) extracted from two days logs of a router of a large service provider network. Namely, the original real data set contains

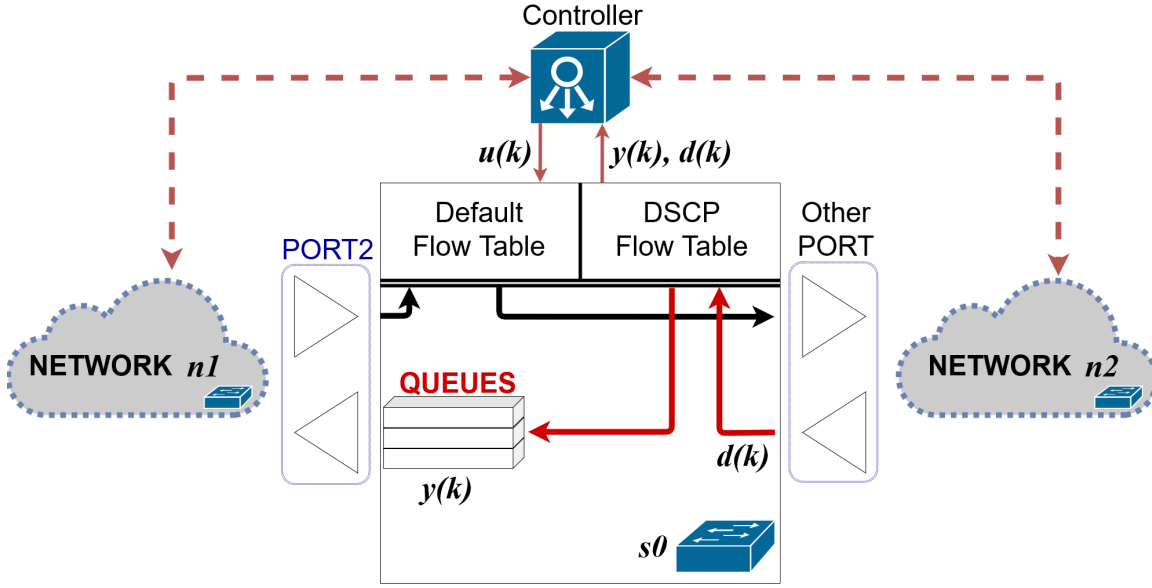


Figure 3.1: Mininet emulated network architecture.

traffic of a real network incoming from a source geographic area and terminating in a destination geographic area, and is divided for each value of Differentiated Services Code Point (DSCP) with a sampling time of 5 minutes [141, 142]. We recall that DSCP is the modern definition of the Type of Service (ToS) field, in which the first 6 bits are the Differentiated Services field that are in common with ToS field, and the last 2 bits regard explicit congestion notification. The ToS field can specify the priority of a datagram and the request for a low delay addressing, a high throughput or a high reliability service. Following the implementation of many national service provider networks (see e.g. [143]), we partition the 8 different values of the DSCP in three classes: the *Default* class (DSCPs 0, 1, 3), the *Premium* (DSCPs 2, 4, 6, 7), and the *Gold* class (DSCP 5): to each class we will assign a single queue, associated with a different priority.

Using D-ITG Sender and Receiver SW modules it has been possible to establish a connection between networks $n1$ and $n2$. In particular, 16 ITG modules have been initialized: 8 for each network, and within each network one for each DSCP index. These modules handle the sampling time interval (5 minutes), the inter-departure time stochastic distribution associated with the packet rate, the packet size stochastic distribution, the IP and port destinations, and the DSCP index. Regarding the controller SW module we used Ryu, which provides software components with well defined Application Programming Interfaces (API) that give the possibility to easily create new network management and control applications. Ryu supports various protocols for managing network devices, such as OpenFlow, Netconf, OF-config, etc. About OF, Ryu supports fully 1.0, 1.2, 1.3, 1.4, 1.5 and

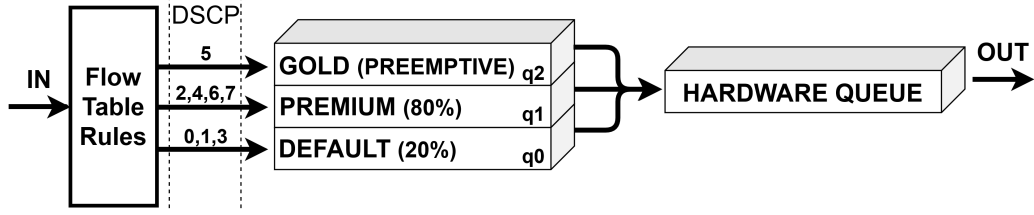


Figure 3.2: Static queues rate with routed packets relative to DSCP.

Nicira Extensions. For our test-bed the 1.3 version has been chosen. In particular, APIs were used for queue control and counter recovery from the switches [144, 145]. The feedback information collected for the purposes of this work are the descriptions of switches, ports and queues, the number of packets received and transmitted on each port of a switch, the packets passing through the flow tables, the packet rate values of each queue and the packets transmitted by each single queue. In summary, the variables associated to the traffic and control signals in our closed-loop architecture are as follows:

- $d(k) \in \mathbb{R}^{10}$ is a measurable disturbance vector, i.e. representing variables we cannot control. The first 8 components $d_1(k), \dots, d_8(k)$ consist of the number of packets incoming in the switch s_0 differentiated with respect to the 8 different values of the DSCPs. $d_9(k)$ and $d_{10}(k)$ are proxy variables, i.e. the hours and minutes of the day, which are very useful to the predictive model since traffic dynamics are tightly correlated with them, e.g. they are substantially different between night and day;
- $y(k) \in \mathbb{R}^3$ is the measured output vector, i.e. the variables we want to regulate. They consist of the number of packets outgoing from switch s_0 differentiated with respect to the corresponding service class: $y_1(k)$ is the Default Queue output, $y_2(k)$ is the Premium Queue output and $y_3(k)$ is the Gold Queue output;
- $u(k) \in \mathbb{R}^3$ is the control input vector. Each component corresponds to the queue configuration of each service class: $u_1(k)$ is the Default Queue configuration, i.e. the maximum admitted bandwidth; $u_2(k)$ is the Premium Queue configuration, i.e. the maximum admitted bandwidth; $u_3(k)$ is the Gold Queue configuration, i.e. the minimum admitted bandwidth;

In this work we first applied in our emulative scenario the static control of queues used in the Italian service provider network of *Telecom Italia* [143], which is depicted in Figure 3.2. To this aim we defined 3 queues in s_0 and configured the queues as follows: packets with the DSCP values 0, 1 and 3 (Default queue) are routed via queue 0, with maximum rate $u_1(k) = 20MB/s, \forall k$; the packets with values 2, 4, 6 and 7 (Premium queue) are routed

on queue 1, with maximum rate $u_2(k) = 80MB/s, \forall k$; the packets with value 5 (Gold queue) are routed on queue 2, with minimum rate $u_3(k) = 100MB/s, \forall k$. To obtain this prioritization it has also been necessary to set the flow tables of $s0$ to discriminate incoming packets based on the DSCP value and the destination IP address, and re-route them to the desired queue. Also, to obtain a bottleneck situation in $s0$, we have chosen the bandwidth of the output port of switch $s0$ at $100 MB/s$. Using this configuration queue 2 uses the maximum capacity of the port to forward packets with preemptive priority, while the other two queues use the remaining bandwidth from $0 MB/s$ to the specified maximum bandwidth based on needs. To instantiate the chosen topology in Mininet it has been necessary to run the A.8 code from the Ubuntu command line with the following text:

```
sudo python Topology_qos.py
```

In this script all network devices (remote controller, switches and hosts), their attributes and their connections are defined. Furthermore this script is also responsible for the traffic generated between hosts thanks to the function defined within the A.9 code that is iteratively used every five minutes to read the provided real data traffic database and generate the synthetic traffic inside the network. In lines 49 to 53 of A.8 code Mininet adds an external controller, Ryu in our case, to specified IP address and port. Obviously it is necessary that the controller is already instantiated before launching the network topology, and it is possible to do this through the following command:

```
ryu run main_controller_TOS.py rest_qos.py rest_conf_switch.py ofctl_rest.py
```

This command executes several scripts, the first one (A.1) is the Ryu controller which invokes additional functions designed for saving network information and setting queue bandwidths (from A.2 to A.4). The remaining scripts are all the rest APIs required for these features to work properly (A.5, A.6 and A.7 codes).

As we will see in Section 3.3, using static priority control the queues will not be able to send all the packets incoming from network $n1$, and a dramatic amount of packets will be lost. This motivates the application of optimization techniques, which are enabled by the predictive models derived using the methodology described in section 3.2.

3.2 Regression Trees and Random Forest based models for MPC

In this section a methodology to apply the results proposed in [146, 147] is illustrated, to identify, starting from a set of collected historical data $\mathcal{D} = \{y(k), u(k), d(k)\}_{k=0}^{\ell}$ (generated as described in the previous section), a switching ARX model of the input-output

behavior of the traffic flow in a switch of a SDN network as follows:

$$x(k+j+1) = A'_{\sigma_j(x(k),d(k))}x(k) + \sum_{\alpha=0}^j B'_{\sigma_j(x(k),d(k)),\alpha}u(k+\alpha) + f'_{\sigma_j(x(k),d(k))}, \quad (3.1)$$

$j = 0, \dots, N-1$, where $x(k) \doteq [y^\top(k) \cdots y^\top(k-\delta_y) u^\top(k-1) \cdots u^\top(k-\delta_u)]^\top \in \mathbb{R}^{n_x}$ is an extended state to characterize a switching ARX model, with $x_\iota(k) \doteq [y_\iota(k) \cdots y_\iota(k-\delta_y) u^\top(k-1) \cdots u^\top(k-\delta_u)]^\top \in \mathbb{R}^{\delta_y+1+3\delta_u}$, $\iota = 1, 2, 3$, N is the chosen future predictive horizon, and $\sigma_j : \mathbb{R}^{n_x+10} \rightarrow \mathcal{M} \subset \mathbb{N}$ is a switching signal that associates an operating mode in a finite set \mathcal{M} to each pair $(x(k), d(k))$ and each prediction step j of the horizon. It is possible to directly use model (3.1) to setup the following problem, which can be solved using standard Quadratic Programming (QP) solvers:

Problem 1

$$\begin{aligned} & \underset{u_0, \dots, u_{N-1}}{\text{minimize}} && \sum_{j=0}^{N-1} \left((x_{j+1} - x_{\text{ref}})^\top Q (x_{j+1} - x_{\text{ref}}) + u_j^\top R u_j \right) \\ & \text{subject to} && x_{j+1} = A'_{\sigma_j(x_0, d_0)}x_0 + \sum_{\alpha=0}^j B'_{\sigma_j(x_0, d_0), \alpha}u_\alpha + f'_{\sigma_j(x_0, d_0)} \\ & && u_j \in \mathcal{U} \\ & && x_0 = x(k), d_0 = d(k) \\ & && j = 0, \dots, N-1. \end{aligned}$$

As it is well known [148], Problem 1 is solved at each time step k using QP to compute the optimal sequence u_0^*, \dots, u_{N-1}^* , but only the first input is applied to the system, i.e. $u(k) = u_0^*$. Note that, for any prediction step j , x_{j+1} only depends on the measurements $x_0 = x(k), d_0 = d(k)$ at time k , since they are the only available measurements at time-step k .

3.2.1 RT and RF background

Let us consider a dataset $\{y(k), x_1(k), \dots, x_\eta(k)\}_{k=0}^\ell$, with $y, x_1, \dots, x_\eta \in \mathbb{R}$. Let us suppose to estimate, using Regression Trees, the prediction of the (response) variable $y(k)$ using the values of predictor variables $x_1(k), \dots, x_\eta(k)$. The CART algorithm [149] creates a RT structure via optimal partition of the dataset. It solves a Least Square problem by optimally choosing recursively a variable to split and a corresponding splitting point. After several steps the algorithm converges to the optimal solution, and the dataset is partitioned in hyper-rectangular regions (the leaves of the tree) R_1, R_2, \dots, R_ν . In each partition $y(k)$

is estimated with a different constant \hat{y}_i $i = 1, \dots, \nu$, given by the average of the samples of $y(k)$ falling in R_i , i.e.

$$\hat{y}_i = \frac{\sum_{\{k|(x_1(k), \dots, x_n(k)) \in R_i\}} y(k)}{|R_i|} \quad (3.2)$$

Random Forests [150] are instead an averaging method that exploits a combination of tree predictors such that each tree depends on the values of a random vector sampled independently and with the same distribution for all trees in the forest. The output prediction is given by averaging the predictions provided by all trees in the forest. It is possible to show that the error introduced by the forests quickly and almost surely converges to a limit as the number of trees in the forest becomes large. Such error also depends on the strength of the individual trees in the forest and the correlation between them. Thus, due to the Law of Large Numbers, Random Forests (differently from Regression Trees) do not suffer much variance and overfitting problems. For more details the reader is referred to [149, 150].

3.2.2 Switching ARX (SARX) model identification via RT

To derive a model as in (3.1), a new dataset $\mathcal{X} = \{x(k), u(k), d(k)\}_{k=0}^{\ell}$ has to be defined starting from \mathcal{D} . In order to apply MPC it is needed, for each component of $y(k)$, a model that can predict system's dynamics over a horizon of length N . The idea is to create $3N$ predictive trees $\{\mathcal{T}_{\iota,j}\}$, $\iota = 1, 2, 3$, $j = 0, \dots, N - 1$, each one to predict the 3 outputs components of the system over the N steps of the horizon. To create the tree structure, the RT algorithm (CART) partitions the dataset \mathcal{X} into regions \mathcal{X}_i , such that $\biguplus \mathcal{X}_i = \mathcal{X}$, and assigns to each region a constant value given by the average of the output values of the samples that ended up in that leaf. In run-time, once the trees are created, and given a real-time measurement $(x(k), u(k), d(k))$ belonging to leaf i , the CART algorithm provides as a prediction the averaged value associated to the leaf as in (3.2). However, since the prediction provided by the RT is a constant value, it cannot be used to setup an MPC problem, thus the learning procedure needs to be modified to identify a modeling framework as in (3.7). To this end, \mathcal{X} is partitioned in two disjoint sets $\mathcal{X}_c = \{u(k)\}_{k=0}^{\ell}$ of data associated to the control variables, and $\mathcal{X}_{nc} = \{(x(k), d(k))\}_{k=0}^{\ell}$ of data associated to remaining variables, and then apply the CART algorithm only on \mathcal{X}_{nc} (this is to avoid that the MPC problem turns out into a Mixed Integer Quadratic Program, see [146, 147] for details); thus, $3N$ RTs $\{\mathcal{T}_{\iota,j}\}$ have been created, each constructed to predict the variable $y_{\iota}(k + j + 1)$, and

consequently $x_\iota(k + j + 1)$. In particular, it is associated to each leaf ι, i_j , corresponding to the partition $\mathcal{X}_{nc,\iota,i_j}$, of each tree $\mathcal{T}_{\iota,j}$ the following affine model is associated

$$x_\iota(k + j + 1) = A'_{\iota,i_j}x(k) + \sum_{\alpha=0}^j B'_{\iota,i_j,\alpha}u(k + \alpha) + f'_{\iota,i_j}, \quad (3.3)$$

$$A'_{\iota,i_j} = \begin{bmatrix} a_1 & a_2 & \cdots & a_{\delta_y} & a_{\delta_y+1} & b_{\delta_y+2} & \cdots & b_{\delta_y+1+3(\delta_u-1)} & \cdots & b_{\delta_y+1+3\delta_u} \\ 1 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 1 & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & 1 & \cdots & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 1 & \cdots & 0 \end{bmatrix},$$

$$B'_{\iota,i_j,\alpha} = \begin{bmatrix} b_{1,\alpha} & b_{2,\alpha} & b_{3,\alpha} \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix}, \quad \alpha < j, \quad B'_{\iota,i_j,j} = \begin{bmatrix} b_{1,\alpha} & b_{2,\alpha} & b_{3,\alpha} \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix}, \quad f'_{\iota,i_j} = \begin{bmatrix} f \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad (3.4)$$

where the coefficients of matrices A'_{ι,i_j} , $B'_{\iota,i_j,\alpha}$ and f'_{ι,i_j} are obtained in each leaf ι, i_j by fitting the corresponding set of samples solving the following Least Squares with inequality constraints problem:

Problem 2

$$\begin{aligned} & \underset{\xi_{\iota,i_j}}{\text{minimize}} \quad \|\Lambda_{\iota,i_j}\xi_{\iota,i_j} - \lambda_{\iota,i_j}\|_2^2 \\ & \text{subject to} \quad f_{\min} \leq f \leq f_{\max} \\ & \quad \quad \quad a_{\min} \leq a_j \leq a_{\max} \\ & \quad \quad \quad b_{\min} \leq b_{\iota,\alpha} \leq b_{\max}, \end{aligned} \quad (3.5)$$

where ξ_{ι,i_j} , λ_{ι,i_j} , and Λ_{ι,i_j} contain respectively the parameters of matrices in (3.4), the predictions $x_\iota(k + j + 1)$, and the current measurements of $x(k)$ and $u(k + \alpha)$. Linear

inequalities (3.5) are used to constrain elements in ξ_{ι, i_j} to take into account physical system constraints and improve prediction accuracy. Model (3.3) can be easily compacted in the following form taking into account all the states $\iota = 1, 2, 3$:

$$x(k+j+1) = A'_{i_j} x(k) + \sum_{\alpha=0}^j B'_{i_j, \alpha} u(k+\alpha) + f'_{i_j}. \quad (3.6)$$

In particular, with the specific choice of $\delta_u = 0$ model (3.1) can be rewritten in the following state-space formulation

$$x(k+j+1) = A_{\sigma_j(x(k), \mathbf{u}^-(k), d(k))} x(k+j) + B_{\sigma_j(x(k), \mathbf{u}^-(k), d(k))} u(k+j) + f_{\sigma_j(x(k), \mathbf{u}^-(k), d(k))}, \quad (3.7)$$

where $\mathbf{u}^-(k) = [u^\top(k-1) \cdots u^\top(k-\delta)]^\top$ is the vector with the regressive terms of the input used to only grow the trees, and $\sigma_j : \mathbb{R}^{3(\delta_y+1)+3\delta+10} \rightarrow \mathcal{M} \subset \mathbb{N}$. Thanks to this new formulation the following proposition shows that model (3.6) is equivalent to model (3.7) for any initial condition, any switching signal and any control sequence.

Proposition 1 [147] *Let A'_{i_j} , $B'_{i_j, \alpha}$ and f'_{i_j} , $\alpha = 0, \dots, j$, $j = 0, \dots, N-1$, be given. If A'_{i_j} is invertible for $j = 0, \dots, N-1$, then there exists a model in the form*

$$\bar{x}(k+j+1) = A_{\sigma_j(\bar{x}(k), \mathbf{u}^-(k), d(k))} \bar{x}(k+j) + B_{\sigma_j(\bar{x}(k), \mathbf{u}^-(k), d(k))} u(k+j) + f_{\sigma_j(\bar{x}(k), \mathbf{u}^-(k), d(k))}$$

such that for any initial condition $\bar{x}(k) = x(k) = x_k$, any switching sequence i_0, \dots, i_{N-1} and any control sequence $u(k), \dots, u(k+N-1)$, then $\bar{x}(k+j+1) = x(k+j+1)$, $\forall j = 0, \dots, N-1$.

As discussed in [147], from experimental findings it is possible to notice that the contribution in terms of model accuracy introduced by the choice of $\delta_u = 0$ is negligible, since previous control inputs are already considered in the tree structure choosing $\delta > 0$. Thus, in the rest of the thesis it will be considered $\delta_u = 0$ and $\delta > 0$, i.e. only the regressive terms of the input in the tree structure learning will be used and not in the state definition.

3.2.3 SARX model identification via RF

RF-based models can be constructed exploiting the RT-based formulation: in particular, let us consider $3N$ RFs $\mathcal{F}_{\iota, j}$, $\iota = 1, 2, 3$, $j = 0, \dots, N-1$. For each tree $\mathcal{T}_\tau^{\mathcal{F}_{\iota, j}}$ of the forest $\mathcal{F}_{\iota, j}$, it is possible to estimate the coefficients a_* , b_* and f in (3.4) for each leaf ι, j, i_τ , i.e. $\tilde{\xi}_{\iota, j, i_\tau}$, solving Problem 2. With a small abuse of notation, let us indicate by $|\mathcal{F}_{\iota, j}|$ the

number of trees in the forest ι, j . Then $\forall \iota, j$, the parameters to build matrices in (3.9) can be obtained by averaging parameters a_* , b_* and f , $\forall \tau = 1, \dots, |\mathcal{F}_{\iota,j}|$, i.e.

$$\tilde{\xi}_{\iota,j} = \frac{\sum_{\tau=1}^{|\mathcal{F}_{\iota,j}|} \tilde{\xi}_{\iota,j,i_\tau}}{|\mathcal{F}_{\iota,j}|}, \quad (3.8)$$

over all the trees of forest $\mathcal{F}_{\iota,j}$. At this point, starting from (3.3), it can be easily construct the following model, as in (3.6) to be used in the MPC formulation by combining for $\iota = 1, 2, 3$ the matrices in (3.4) coming either from the RTs or from the RFs:

$$x(k+j+1) = A'_{i_j} x(k) + \sum_{\alpha=0}^j B'_{i_j, \alpha} u(k+\alpha) + f'_{i_j}. \quad (3.9)$$

3.2.4 MPC problem formulation.

Model (3.9) is used to formalize Problem 1 according to the SDN priority queueing problem:

Problem 3

$$\begin{aligned} & \underset{\mathbf{u}}{\text{minimize}} && \sum_{j=0}^{N-1} \left[(x_{j+1} - x_{\text{ref},j})^\top Q (x_{j+1} - x_{\text{ref},j}) + u_j^\top R u_j \right] \\ & \text{subject to} && x_{j+1} = A_{\sigma_j(k)} x_j + B_{\sigma_j(k)} u_j + f_{\sigma_j(k)} \\ & && \Delta u_\iota^{\min} \leq u_{\iota,j} - u_{\iota,j-1} \leq \Delta u_\iota^{\max} \\ & && u_\iota^{\min} \leq u_{\iota,j} \leq u_\iota^{\max} \\ & && u_{1,j} + u_{2,j} \leq 100 \\ & && x_0 = x(k), \mathbf{u}_0^- = [u^\top(-1) \cdots u^\top(-\delta)]^\top, d_0 = d(k), \\ & && j = 0, \dots, N-1, \iota = 1, 2, 3, \end{aligned}$$

where $\sigma_j(k) = \sigma_j(x(k), \mathbf{u}^-(k), d(k))$ (with a slight abuse of notation), $u_{\iota,j}$ is the ι^{th} component of the input u at time $k+j$; Δu_ι^{\min} and Δu_ι^{\max} are used to limit large variations on the inputs in 2 consecutive steps, in order to avoid that the queues drastically set to the minimum value and thus potentially increase packet losses during the next period; u_ι^{\min} and u_ι^{\max} define the bandwidth limits induced by the QoS requirements of the corresponding priority class. At each time step k the measurements of the variables in \mathcal{X}_{nc} are collected, select the current matrices of (3.9) narrowing down the leaves of the trees, for $j = 0, \dots, N-1$, solve Problem (3), and finally apply only the first input of the optimal sequence \mathbf{u}^* found, i.e. $u(k) = u_0^*$.

3.2.5 Disturbance forecast

The knowledge at each time k of the future input traffic $(d(k+1), \dots, d(k+N-1))$ can greatly improve the MPC performance. However, while the future values of the proxy variables (hours and minutes) are clearly well known, the knowledge of the future values of the first 8 component of the disturbance, i.e. number of packets incoming in the switches for each DSCP index are unknown at the current instant k . To address this problem $8(N-1)$ RFs $\mathcal{F}_{\iota,j}^d$, $\iota = 1, \dots, 8$, $j = 0, \dots, N-1$ have been built in order to provide a prediction $\hat{d}_\iota(k+j)$ of the 8 disturbance components $d_\iota(k+j)$ over the future time horizon: as widely illustrated in [146, 147] the technique previously described can be easily modified by appropriately redefining the dataset as $\mathcal{X} = \{(x(k), u(k), d(k), \dots, d(k+N-1))\}_{k=1}^\ell$ for the training phase, and considering a switching signal in (3.7) given by $\sigma_j(k) = \sigma_j(x(k), \mathbf{u}^-(k), d(k), \hat{d}(k+1), \dots, \hat{d}(k+j)), \forall j = 0, \dots, N-1$, i.e. also depending at time k on the future input traffic.

3.3 Simulation results

In this section simulation results of the application of the proposed approach to SDN Priority Queueing identification and control will be provided. Standard RFs are used to derive predictive models of the disturbance components $d_1(k), \dots, d_8(k)$, i.e. the switch input differentiated for each DSCP index, and validate the accuracy. Then the validation of accuracy of the predictive model of the output variable $y(k)$ derived as illustrated in Section 3.2 is shown: the predictive models (based on RTs and RFs) will be compared with Artificial Neural Networks, showing that RFs represent the ideal solution both in terms of prediction accuracy and computational complexity; then the effect of iterative dataset updates in the prediction accuracy is illustrated, both with and without prediction of the future disturbances. Finally the proposed predictive models will be used to setup a MPC problem (see Problem 3), and validate the control performance in terms of packet losses reduction and bandwidth saving, both with and without prediction of the future disturbances. It will also be shown, as expected, that using accurate predictive models and applying MPC provides dramatic reduction of packet losses and increase of bandwidth saving with respect to the static bandwidth allocation policy used in Service Provider Networks as described in Section 3.1: even though this result is not surprising, it is decided to quantify the gap to emphasize that much better performance can be obtained in real networks just collecting historical data and applying a controller that can be directly implemented using the accurate models of the proposed identification algorithm and Quadratic Programming solvers (which are well known to be very efficient).

In each of the aforementioned validations, 4 different predictive models have been exploited, using iteratively enriched data sets. More precisely, **OLD** is a predictive model identified with a data set of 5124 samples, collected with a sampling time of 5 minutes and obtained from network emulation with random values of the input $u(k)$; **1UP** is a predictive model identified with the **OLD** data set enriched with 3456 new samples obtained from network emulation when applying closed-loop MPC to define the input $u(k)$; **2UP** is a predictive model identified with the **1UP** data set enriched with 3168 new samples obtained from network emulation when applying closed-loop MPC to define the input $u(k)$; **3UP** is a predictive model identified with the **2UP** data set enriched with 6336 new samples obtained from network emulation when applying closed-loop MPC to define the input $u(k)$. An independent data-set composed by 1684 samples is used to validate the above models. All simulations have been ran on a UDOO x86 Advanced with an Intel Braswell N3160 processor up to 2.24 GHz and 4 GB of RAM [151].

3.3.1 Disturbance predictive model validation

Having an accurate model of the variable $d(k)$ (i.e. the switch input differentiated for each DSCP index) can be helpful to improve the model identification performance as well as the reference input x_{ref} to follow in Problem 3. In this section we apply standard RF algorithms, with a regressive index of 15 steps and 30 trees for each forest, to obtain a predictive model of the disturbance over a predictive horizon of $N = 5$ (25 minutes): this choice of N has been taken considering the tradeoff between time complexity of the identification algorithm and the obtained identification accuracy.

Figure 3.3 shows the Normalised Root Mean Square Error (NRMSE) of the predictive model of the disturbance signals (one for each of the 8 DSCP indices) over a time horizon of $N = 5$: the prediction error is worse for Service 0 (4 – 6%) since it includes the majority of the packets that transit through the switch. For other services the NRMSE is at most 2.2% (Service 7) over all the predictive horizons. The improvement of the model accuracy when using larger (updated) data sets is evident, until a *saturation* is reached and further data do not help to improve the model accuracy: the NRMSE significantly reduces and for Service 0 it is even halved. Figure 3.4 plots, for Service 0 and in a time window of 500 samples (almost two days), the predictions of OLD, 1UP, 2UP and 3UP as well as the original data, and clearly highlights the better prediction of 2UP and 3UP with respect to OLD and 1UP.

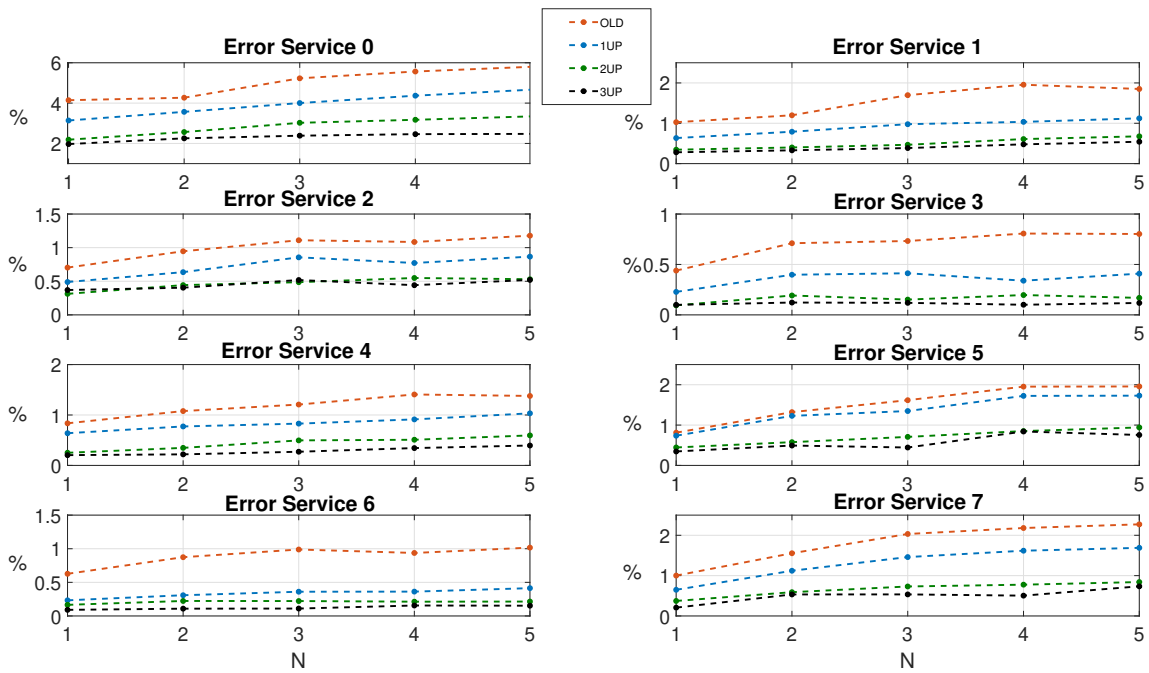


Figure 3.3: NRMSE of the disturbance predictive model over a time horizon of $N = 5$.

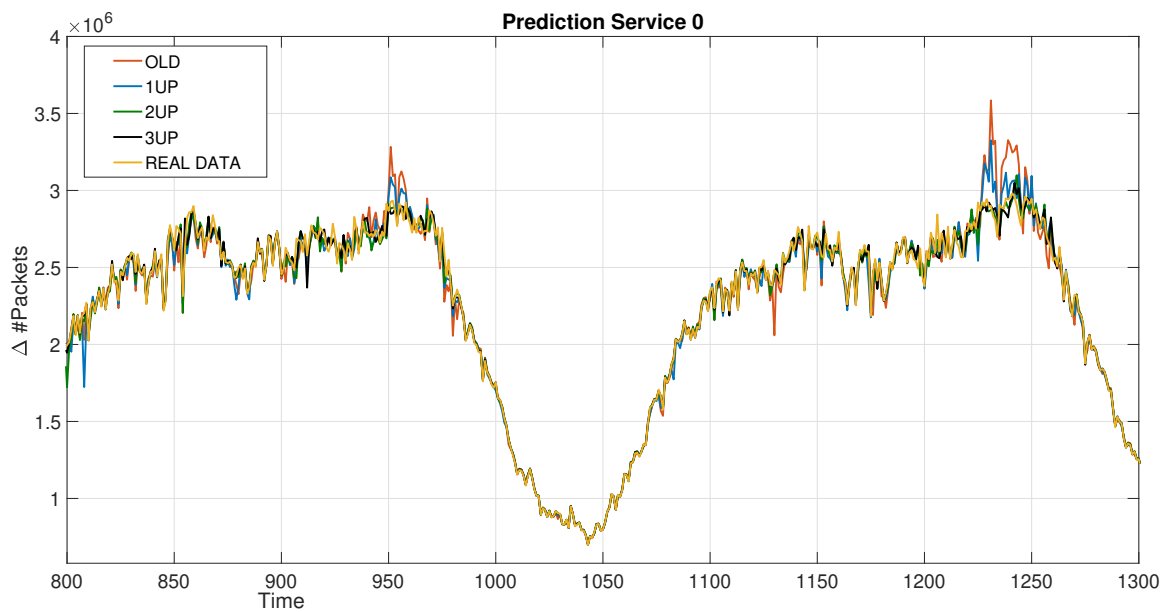


Figure 3.4: Comparison between the real traffic (YELLOW LINE) and the traffic prediction for the different models for Service 0.

3.3.2 Queues predictive model validation

In this section we first compare the accuracy of our predictive models with Artificial Neural Networks. We recall that a neural network is a collection of algorithms that aim to identify underlying relations in a dataset: it consists of groups of connected neurons organized in layers, where the connections between neurons are modeled using weights. The signal produced with this linear composition is then fed into an activation function that is in general nonlinear. The reader is referred to [152] and references therein for more details. A wide number of tools to build Neural Networks have been developed during recent years, e.g. [153, 154, 155] just to mention a few: in this work we exploit the Deep Learning Toolbox of Matlab to compare predictive models based on NNs with the methodology proposed in this work, based on ARX combined RTs and RFs. We consider here just OLD as the learning dataset and chose a predictive horizon $N = 5$.

To identify a RT (resp. RF) based predictive model of the queues we trained a Regression Tree (resp. a Random Forest) for each output and for each time horizon, with a total of 15 trees (resp. 15 forests each consisting of 30 trees). The main parameters used for the identification algorithm (see Section 3.2 and Problem 2) are summarized in Table 3.1. In particular, the regressive terms ($\delta_d, \delta_x, \delta_u$) and the minimum number of samples

Table 3.1: Identification parameters

| Parameters | Value | Parameters | Values |
|----------------------|-------|------------|--------|
| N | 5 | f_{min} | -100 |
| ν | 1 | f_{max} | 100 |
| δ_x | 5 | a_{min} | -100 |
| δ_u | 5 | a_{max} | 100 |
| δ_d | 5 | b_{min} | 0 |
| Minleaf | 13 | b_{max} | 10000 |
| $ \mathcal{F}_{ij} $ | 30 | | |

for each tree of each forest (MinLeaf) have been chosen, with a trial and error approach, considering that very small regressive horizons and very large values for MinLeaf may lead to inaccurate prediction (as they do not provide sufficient information on the past) but very large regressive horizons and very small values for MinLeaf also lead to inaccurate prediction (as they interpolate very old data that might negatively affect the results and produce overfitting).

Regarding specific parameters used for running NN, and for the sake of a fair comparison, we tuned them to obtain the best performance: in particular we considered shallow networks of 2 layers since deeper networks did not improve the accuracy and, instead,

have the negative effect of increasing the sensitivity of the accuracy with respect to the initial conditions of the weights. Among the many algorithms for optimizing the weights of the neurons we exploited the *Scaled conjugate gradient back-propagation* described in [156], which provided the best accuracy with respect to our dataset. Regarding the activation functions, we used both the classical sigmoid function (*LogSig*) and the Hyperbolic tangent sigmoid transfer function (*TanSig*).

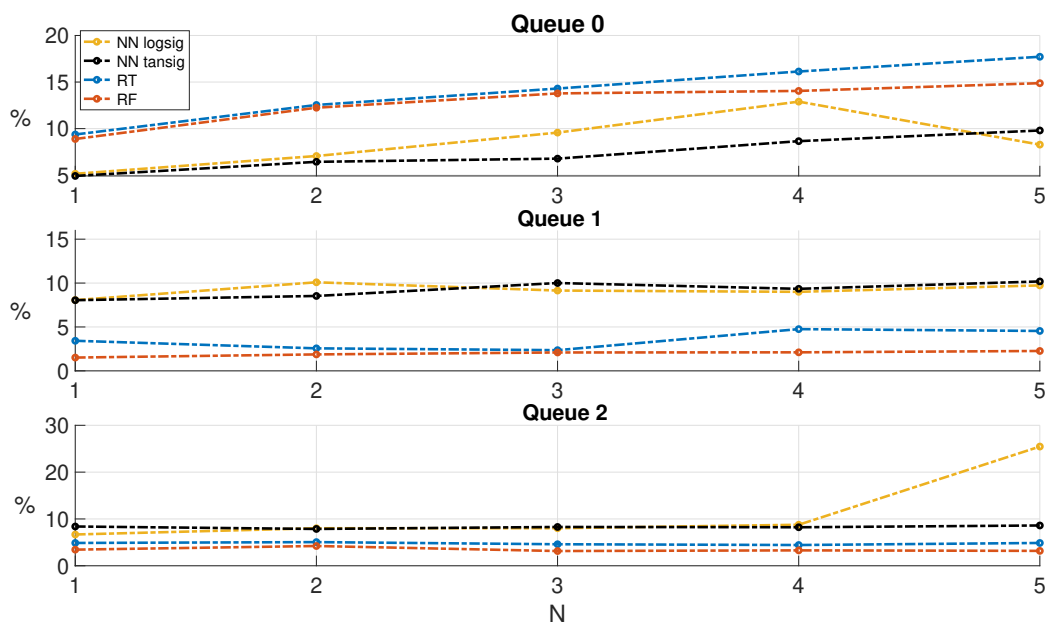


Figure 3.5: NRMSE, up to $N = 5$ and for each priority class, for RT (blue), RF (red), NN with sigmoids as activation function (yellow) and NN with hyperbolic tangent as activation function (black).

As a metric of the prediction accuracy we compared in Figure 3.5 the Normalized Root Mean Square Errors (NRMSE) of the different identification approaches for each priority class and over a horizon up to $N = 5$. Regarding queue 0 (Default) NNs perform better than RT and RF, but in queues 1 (Premium) and 2 (Gold), characterised by higher priority, RF provides the best performance. Queue 0 is characterised by a larger NRMSE with all identification techniques: this is due to the fact that, having the lowest priority, it suffers more packet losses and this can negatively affect the prediction accuracy. Our validation emphasizes that RTs, even though very simple and fast to compute, are often affected by overfitting and variance issues, i.e. small variations of the training data result in large variations of the tree structure and, consequently, of the predictions. Regarding NNs, they provide a less accurate model in 2 cases over 3. Indeed, by analyzing the dataset distribution (see Figure 3.6), we noticed a peculiar regular grid pattern that can be very well approxi-

ated by hyper-rectangles: since RTs and RFs base their prediction on hyper-rectangular dataset partitions, the better performance with respect to NNs is reasonable. For queue 0,

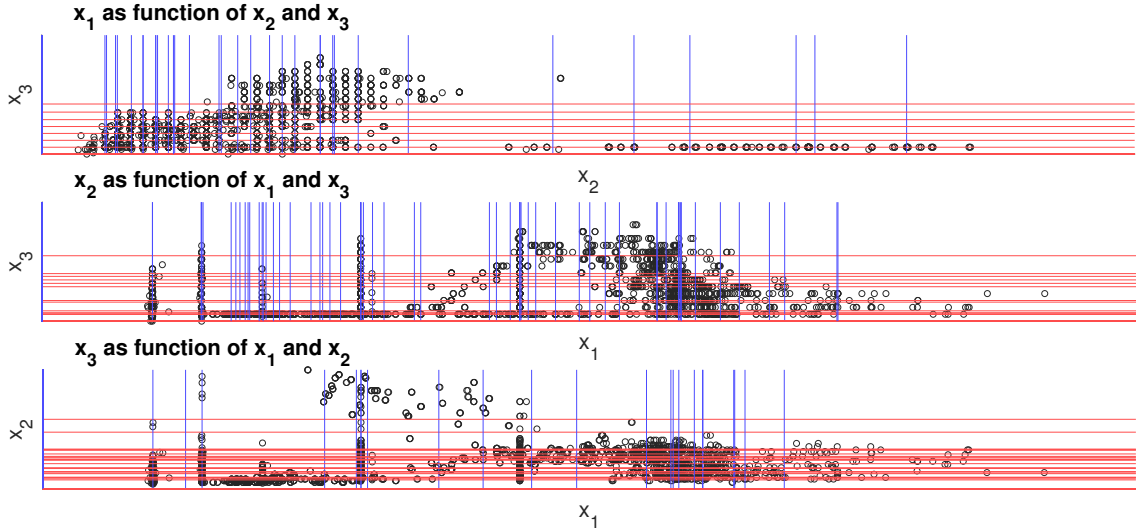


Figure 3.6: Grid pattern emerged from dataset distribution.

even though NNs perform better, we need to remark that their predictive model is based on nonlinear functions: this makes the derived model impractical for real-time control as the corresponding MPC formulation turns into a nonlinear optimization problem, for which there is no approach that can guarantee neither a global optimal solution nor a reasonable computation time. In addition to this, even obtaining a closed mathematical form of the predictive function of a Neural Network starting from neurons and weights is not always an easy task, because of the highly nonlinear interconnections between the different layers. For all these reasons we decided to only use from now on RF-based models, which provide the best choice both from the accuracy and the computational complexity points of view. In the following we illustrate the effect of iterative dataset updates in the prediction accuracy, both with and without knowledge of the future disturbances.

Figure 3.7 and Figure 3.8 plot the NRMSEs respectively without and with knowledge of the future disturbances. The assumption of future disturbance forecast, as expected, provides much better prediction accuracy. The positive effect of updated data sets is also clear, providing accuracy improvements up to 50%: as will be also discussed in the next section, the most relevant prediction accuracy improvement takes place moving from OLD to 1UP or from 1UP to 2UP, while the 3UP model does not improve much.

Remark 1 We wish to highlight that in our simulations we generated data without major modifications of the traffic daily pattern: for this reason enriching the data set converges

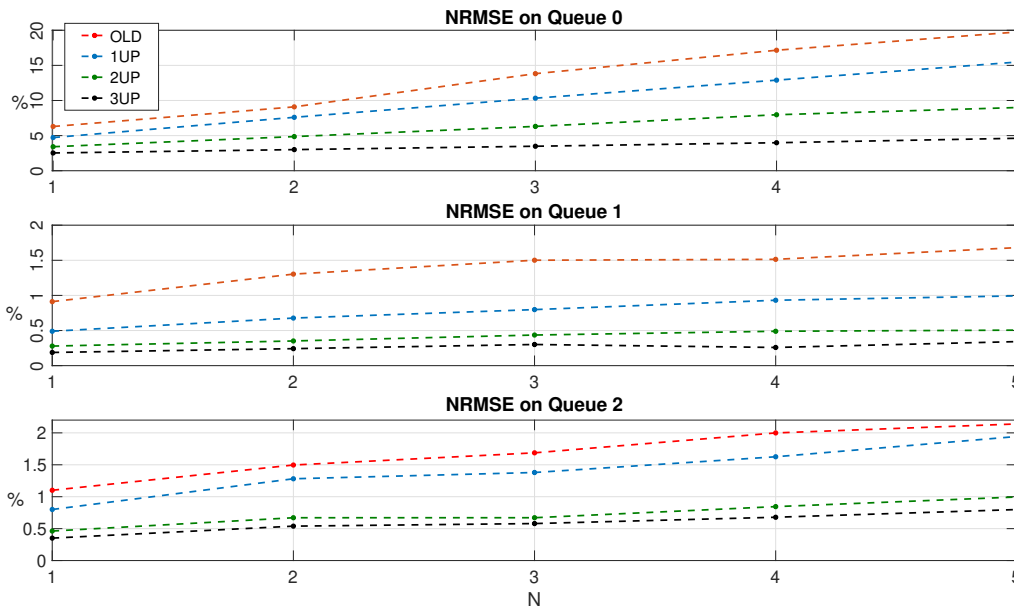


Figure 3.7: NRMSE of the queues output predictive model over a time horizon of $N = 5$, without knowledge of the future disturbances

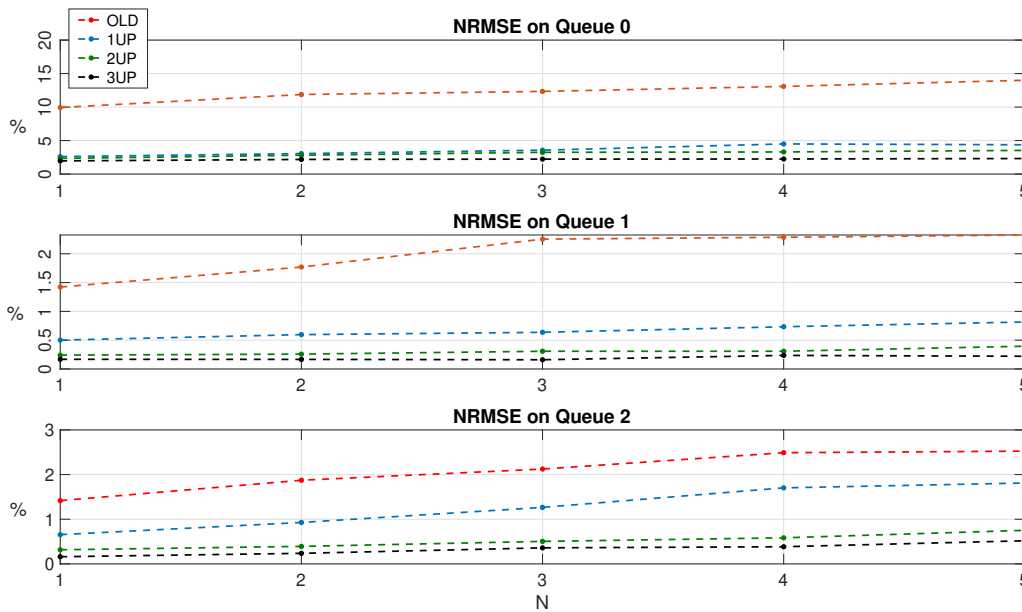


Figure 3.8: NRMSE of the queues output predictive model over a time horizon of $N = 5$, with knowledge of the 4-steps future disturbances

to a saturation of the model accuracy, as discussed above. Nevertheless, the capability of our methodology to iteratively learn from new data is fundamental as, in real life, changes

in the traffic patterns do occur, and model updates are necessary to maintain the model accuracy and the control performance.

3.3.3 Control performance

In this section we setup a control loop where the (Mininet) network emulator and the (Ryu) controller run in two different computers, and synchronize/exchange data using a shared file. Namely, our SW controller module is, in principle, ready to be directly used on a real SDN-based network, with just some minor modifications in the data exchange with the switch devices. The controller implements MPC using the predictive models validated in the previous sections: at each time step, it solves Problem 3 and optimally updates the bandwidth of the different queues. The cost matrices Q and R of Problem 3 respectively weight the output $y(k)$ of the system (i.e. the packet transmission rate for each queue) and the control input $u(k)$ (i.e. the bandwidth assigned to each queue). Since R is required to be positive definite but it makes no sense assigning a penalty to the choice of $u(k)$, we define $R = 10^{-5} \cdot \mathbb{I}$, where the identity matrix \mathbb{I} multiplies a very small value. Matrix $Q = \text{diag}(1, 10^4, 10)$ has been assigned as a diagonal matrix, where the choice of the different diagonal components is related to the priority level of each queue. The remaining constraints of Problem 3 are reported in Table 3.2. In what follows we validate the control

Table 3.2: Constraints in Problem 3

| Parameters | Value | Parameters | Values |
|---------------------|-------|---------------------|--------|
| Δu_1^{\min} | 1 | Δu_1^{\max} | 30 |
| Δu_2^{\min} | 20 | Δu_2^{\max} | 30 |
| Δu_3^{\min} | 20 | Δu_3^{\max} | 20 |
| u_1^{\min} | 10 | u_1^{\max} | 45 |
| u_2^{\min} | 55 | u_2^{\max} | 80 |
| u_3^{\min} | 80 | u_3^{\max} | 100 |

performance both without and with knowledge of the future disturbances. The value of x_{ref} in the optimization problem represents the reference value we chose for tracking system output: indeed, as we wish to minimize packet losses, we minimize the difference between the packets received by the hosts $d(k)$ and those transmitted by the queues $y(k)$ over the horizon N . In case we have no knowledge of future disturbances, we consider x_{ref} equal to the current disturbance measurement $d(k)$ and constant over all the predictive horizon; if instead we have knowledge of future disturbances, we consider x_{ref} equal to such future disturbances. In this section we decided to only compare models OLD, 1UP and 2UP, since model 3UP does not provide any substantial improvement.

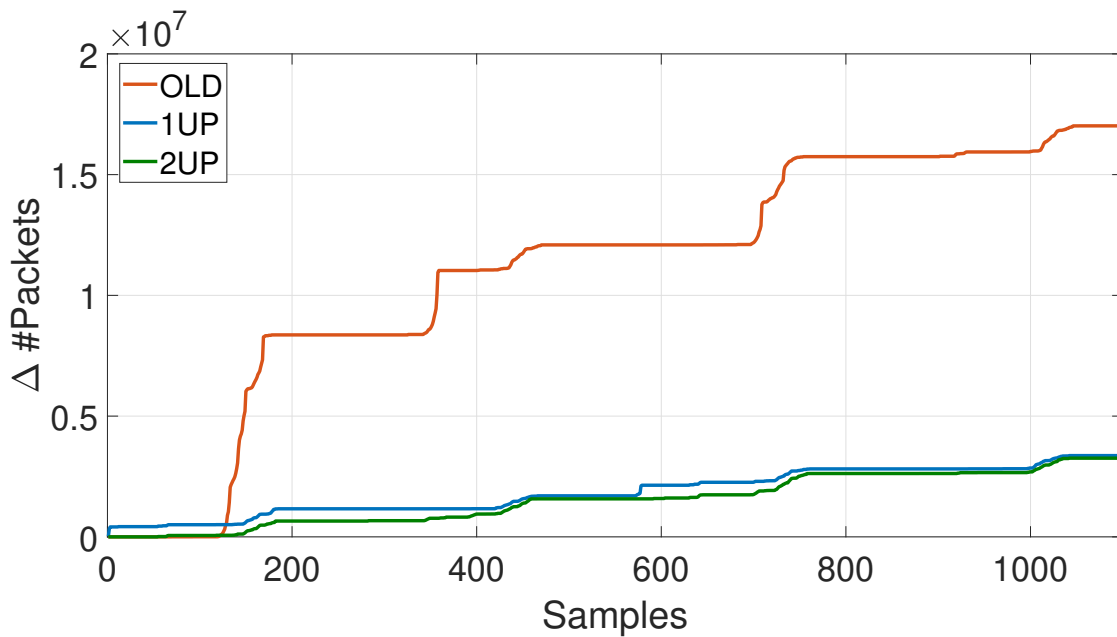


Figure 3.9: Cumulative Packet Losses without knowledge of the future disturbance.

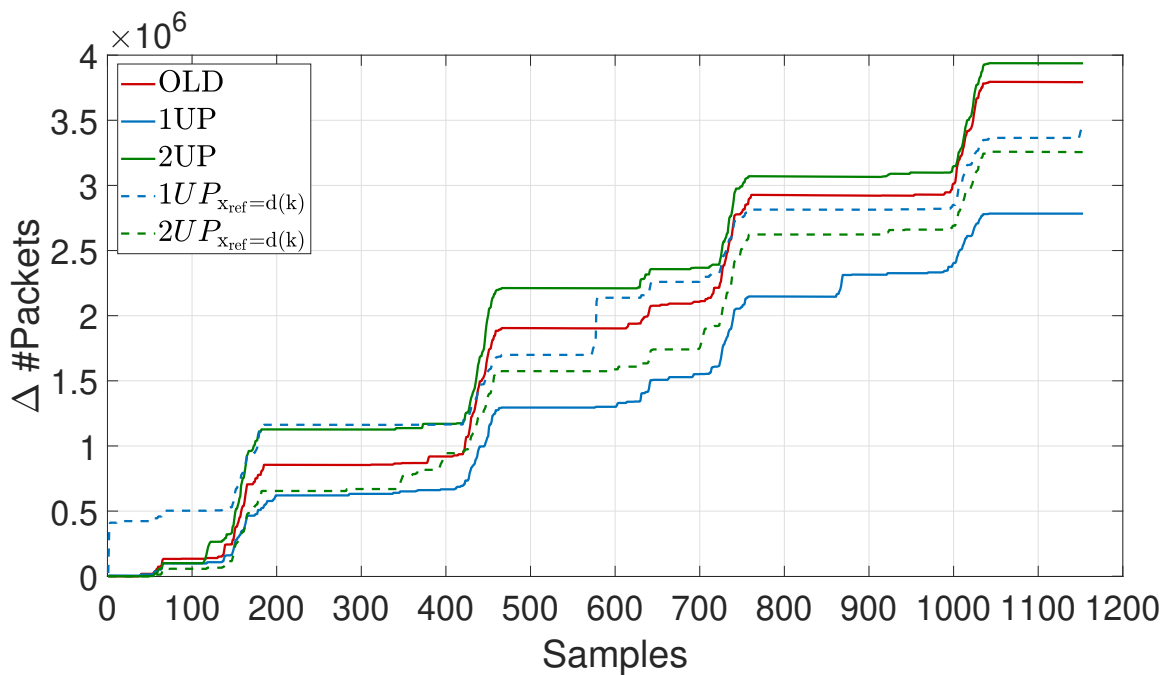


Figure 3.10: Comparison between Cumulative Packet Losses with (solid lines) and without (dashed lines) knowledge of the future disturbance.

Figures 3.9 and 3.10 plot the cumulative packet losses respectively without and with knowledge of the future disturbances. The packet loss rate when the control is performed exploiting the OLD model and without disturbance forecast is around 123% larger than all

other cases (and, of course, incomparably smaller than the static control case [143]). It is also clear from the plots that 1UP and 2UP without disturbance forecast and OLD, 1UP and 2UP with disturbance forecast provide very similar performance. Our interpretation is that OLD models without disturbance forecast have not enough information to provide good accuracy, but they can be easily improved either with a data set update (which however requires 10 days for 1UP and 20 days for 2UP of additional data) or using a predictive disturbance model.

Figure 3.11 illustrates the bandwidth savings showing the recurrence of the different bandwidth usage during the simulations, respectively without and with knowledge of the future disturbances. Without disturbance forecast we exploited up to $25MB/s$ using the OLD model, while we exploited at most $22MB/s$ and $21MB/s$ respectively for models 1UP and 2UP. Using disturbance forecast, as expected, even less bandwidth is exploited.

We conclude this thesis by quantifying the gap between priority queueing control performance of MPC, obtained solving Problem 3 and based on our RF predictive model, with the static control policy adopted by service provider networks in [143]. Figure 3.12 highlights the dramatic improvement of MPC with respect to static control: the red line shows the incoming traffic, the blue line shows the sum of the packets sent from the queues, and their difference represents packet losses. Until the $400th$ static control has been implemented as in [143], generating many packet losses due to queues saturation. From that sample to the end of our experimentation we implemented MPC using our RF-based model, drastically reducing packet losses: quantitatively, after 700 sampling periods the cumulative number of dropped packets with the static policy is about $5.5 \cdot 10^8$ versus $6.6 \cdot 10^6$ with MPC, with a decrease of $5.434 \cdot 10^8$ lost packets (-88%). We remark that, even though the improvement of MPC with respect to static control is not surprising, much better performance can be obtained in real networks just collecting historical data and applying a controller that can be directly implemented using the accurate models of our identification algorithms and Quadratic Programming standard solvers.

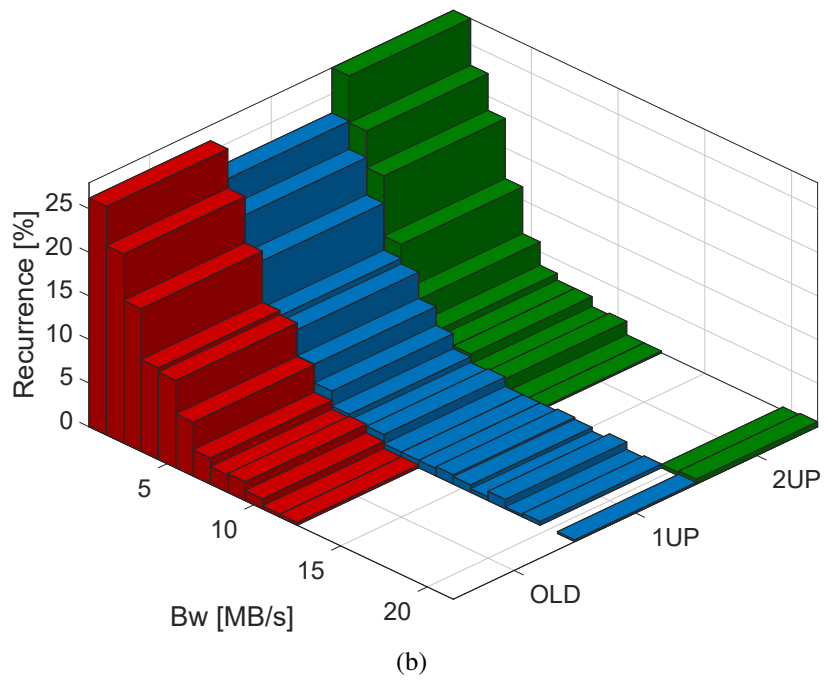
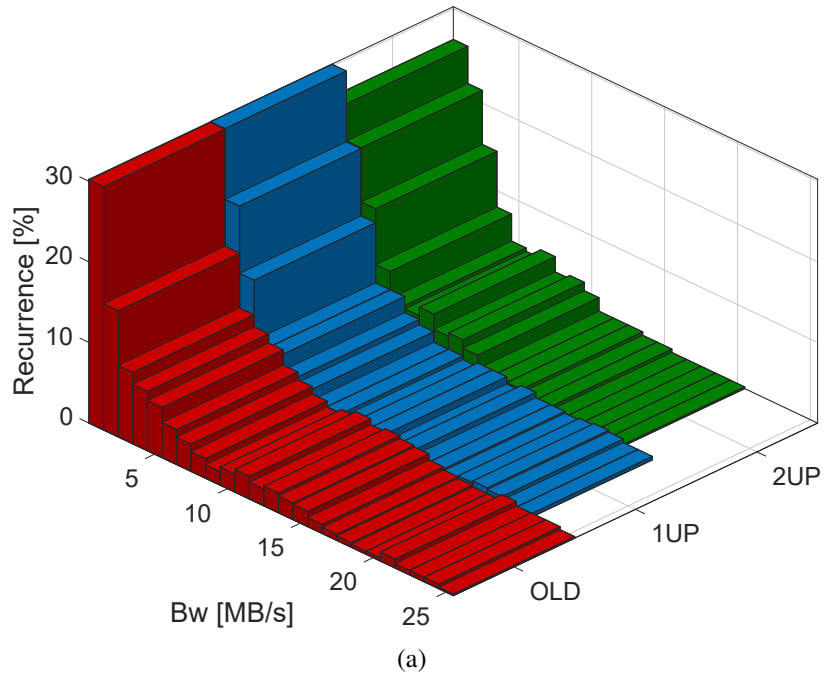


Figure 3.11: Bandwidth saving comparison without (a) and with (b) knowledge of the future disturbances.

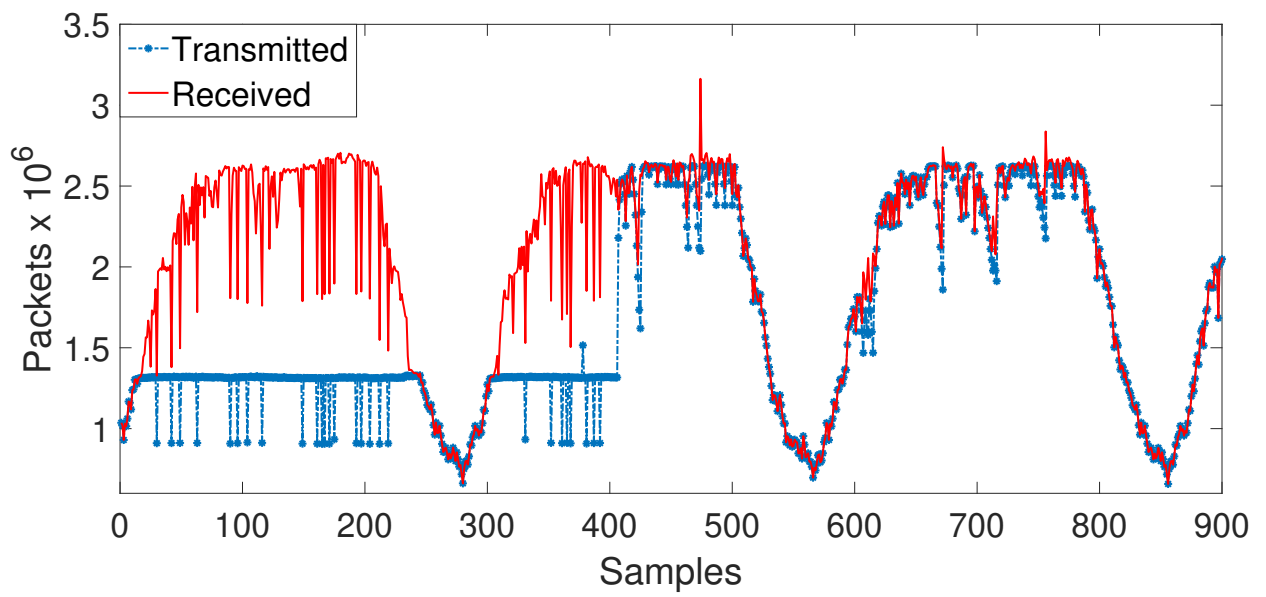


Figure 3.12: Static controller up to the 400th, then MPC controller.

Chapter 4

RT- and RF-based predictive models of multi-service traffic in a real Service Provider Network

This chapter shows how to apply the methods presented in Chapter 3 to derive a predictive model of multi-service traffic in a real network with dedicated hardware. We finally validate the performance of the derived predictive models on the traffic obtained from an Italian internet service provider (Sonicatel S.r.l.).

4.1 Control performance validation over dedicated hardware network

Given the limitations of the Mininet software, it has been decided to test the previously explained algorithms on a real network. Due the fact that the SDN network devices are much expensive, it has been chosen to take an intermediate step in which each device is associated with a dedicated hardware (unlike Mininet, where multiple virtual devices shared single hardware resources). The used architecture is shown in Figure 4.1, where two Raspberry pi 3 [157] have been used as hosts connected on a single switch. The SDN switch resides in a third Raspberry, where the firmware of an OVS has been installed and two ethernet/usb adapter have been used as ethernet ports (eth1 and eth2) to connect the hosts. The built in ethernet port (eth0) has been used to connect the SDN controller (RYU) to the switch. An Arduino UNO with a DS1307 module has been used to share single time schedule from the controller to the hosts. By using the python script in B.6 it has been possible to iteratively update the time on DS1307 module every hour, then each raspberry can update its internal time by asking the time to module via I^2C serial communication. Every update is performed in different minutes of the same hour to avoid

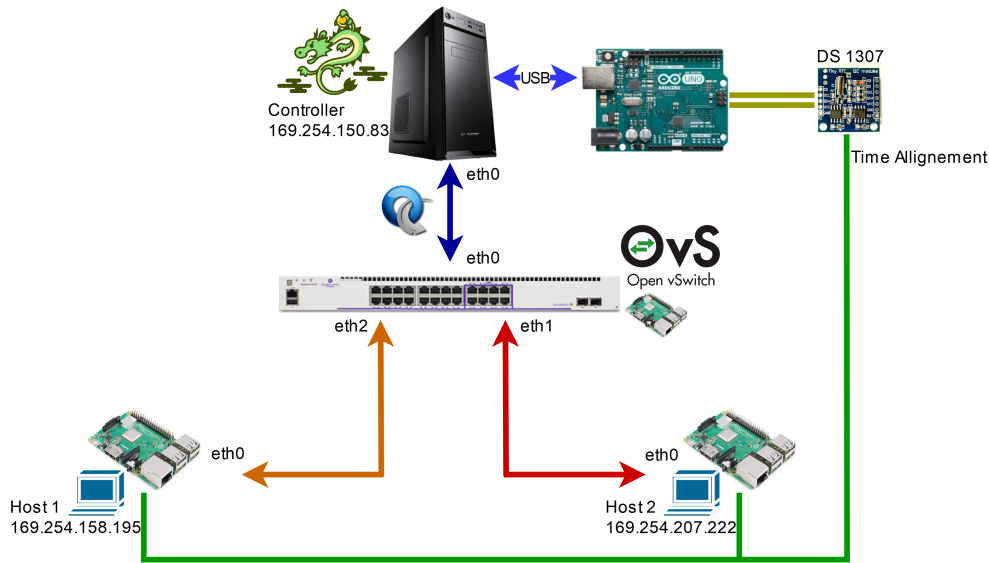
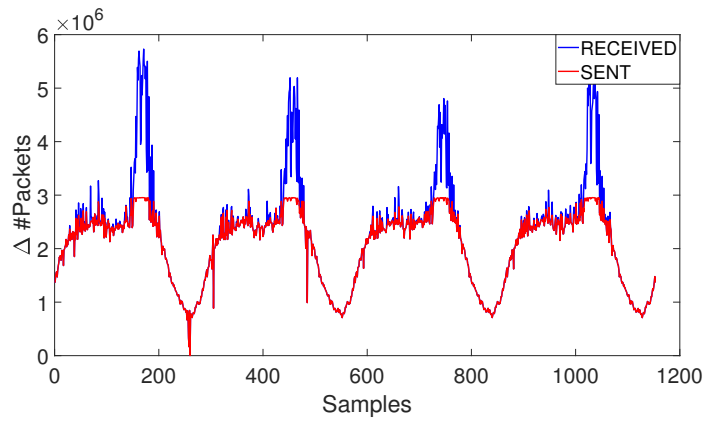


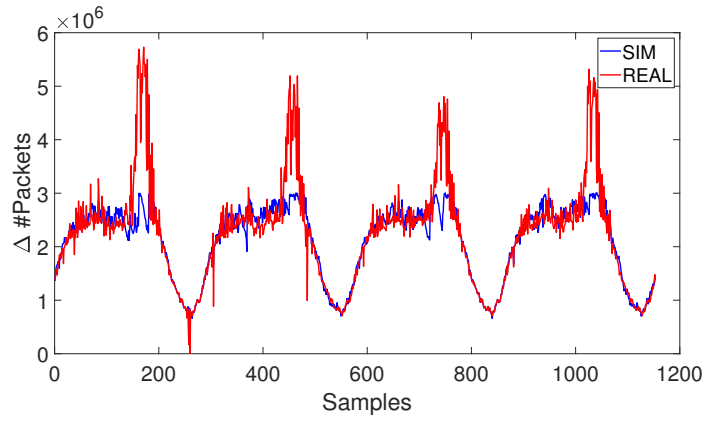
Figure 4.1: Network architecture with dedicated hardware devices.

collisions caused by multiple requests. This time sharing has been necessary to ensure time synchronization between traffic generation and data harvesting. In a real network the time synchronization is ensure to internet time sharing. Even in this environment a Ryu controller has been used as SDN controller with the same Python script previously described for the Mininet network (e.g. A.2, A.1 and A.3). The custom flow table rules are set after the deployment of the controller and after the join of the switch by a single run of the code in B.4. With this operation we have the default set up as in section 3.1 (e.g. three queues on port 2 with a bandwidth of $100Mbps$ and 20% of port bandwidth for queue 0, 80% of port bandwidth for queue 1 and 100% of port bandwidth for queue 2). While for the Mininet emulator we had a single code in which both the network topology and the traffic generation of each host were present (e.g. A.8), in the case of dedicated hardware it was necessary to write a new Python script that included the generation and reception of traffic and infinitely run it on the two Raspberry, which act as hosts. The code B.1 contains two different threads: the first one is very similar to the part of code contained in A.8 for the generation of the traffic, the only difference is the IP address of the hosts. The second thread is very simple and is needed to start the DITG Receiver module on each host. After some tests it has been possible to see that in the hours characterized by a larger number of packets incoming in the switch the computational capacity of a Raspberry pi 3 is not sufficient to elaborate all the necessary operations to route the packets to the hosts. Thus it has been decided to send packets only from *Host2*, with IP address 169.254.207.222, to *Host1*, with IP address 169.254.158.195. With this traffic generation no anomaly was found on the information obtained from the OF counters as showed in

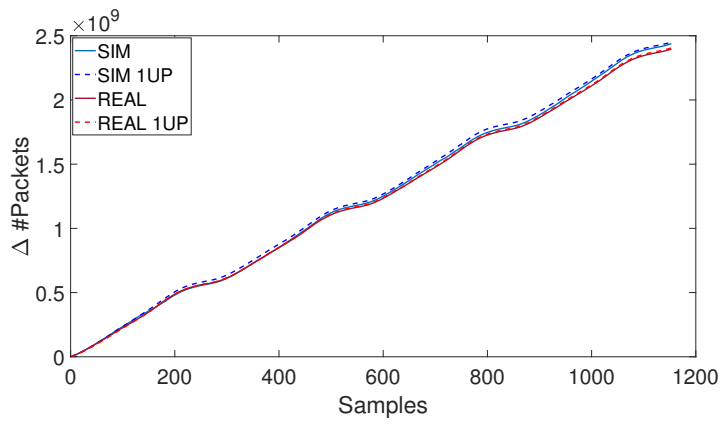
Figure 4.2(a). This figure shows packets coming into the switch generated by *Host2* (blue line) and packets outgoing from port 2 of the switch to *Host1* (red line), in case the MPC control policies explained in Section 3.2 are applied with the same mathematical model used in Section 3.3.3. This figure makes it clear that the traffic generation is different than the traffic generated by virtual hosts in Mininet. In particular, in the last hours of the day it is possible to notice a larger traffic peak than in the emulation environment, as shown in Figure 4.2(b). This is probably caused by sharing multiple network devices on a single hardware, which decreases the performance of each network element. With this traffic generation differences is difficult to compare the results obtained from those environment. Due the chosen limitations of the queues bandwidth it has been possible to see in Figure 4.2(c) that the amount of packets transmitted from the controlled port is about the same between the two network setups, even after one model update like the one explained in Section 3.3. This last very important result demonstrates how it is possible to use a virtual network to train a mathematical model aimed to controlling some device features and then apply this controller to a likely real network while maintaining the same traffic profile. Furthermore, another interesting aspect that emerges from these data is that even after an update of the control model, therefore after adding a traffic profile different from the one already present, the overall behavior of the queues remains practically unchanged. This set of results paves the way for experimentation on real networks.



(a)



(b)



(c)

Figure 4.2: Packets that transit inside the switch (a), comparison between packets incoming in the switch in emulation environment and in dedicated hardware (b) and sum of packets sent by the switch port with different control model (c).

4.2 Traffic predictive model validation on Italian Internet provider network

In addition to the validation of our predictive models of the incoming traffic over the Mininet environment and dedicated hardware devices network, the accuracy has been also tested on data measured from a real network device (Ubiquiti EP-16) of an Italian internet provider (Sonicatel S.r.l.). Data collection has been performed using the software Cacti [158].

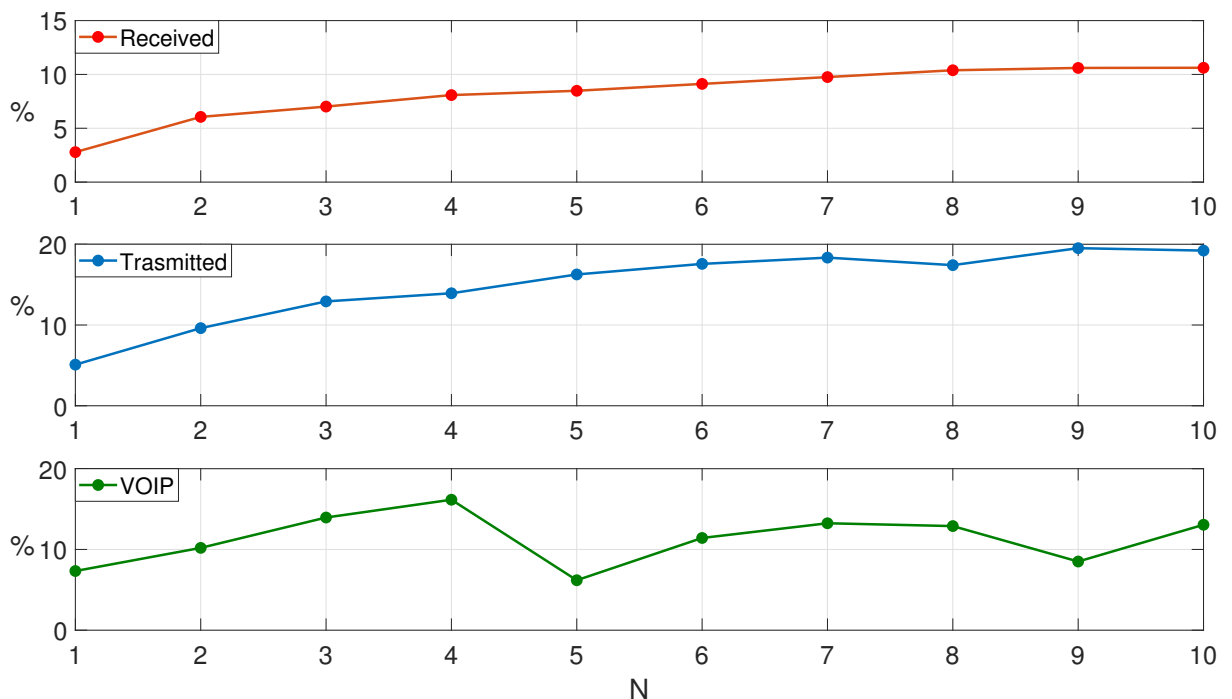


Figure 4.3: NRMSE of the packets predictive model over a time horizon of $N = 10$.

Since this device is part of a running commercial network, some constraints in data collection have forced to only measure the sum of all packets entering and leaving the device, and it has been possible to extract from such traffic only incoming VOIP packets: i.e., it has not been possible to extract packets differentiated for each DSCP. Moreover, it is not currently possible to apply any type of closed-loop control on the network device. For the above 2 reasons the control performance has not been validated.

About data analysis, 53 days of data measurements have been used for RF training and about 3 days for model validation. Figure 4.3 shows the prediction on three classes of packets: all packets received, all packets transmitted, VOIP packets received. The plots

show that our methodology provides a very accurate prediction even on a real internet service provider network.

After few months it has been possible to extend our trained model, using a total of 26138 samples, with the same method previously explained in section 3.3. This model has been validated on a test of 19144 samples, i.e. on more than two months of measurements. Even though the test pool is so large, thanks to the variety of train data it has been possible to obtain very low error values on packet prediction, as shown in Figure 4.4.

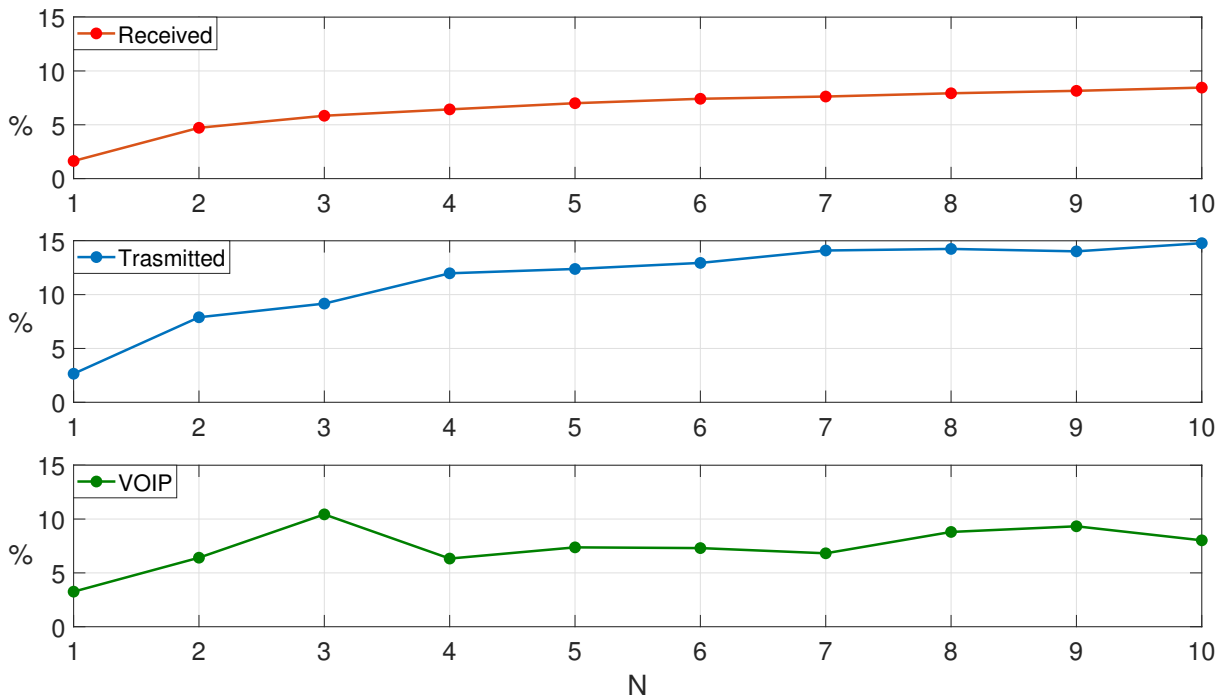


Figure 4.4: NRMSE of the packets predictive model over a time horizon of $N = 10$ after one data update.

At a later time Sonicatel S.r.l. needed to move the monitored device to another location on their network by connecting different users with different contracts and therefore with different traffic profiles. This has been a great opportunity to validate the proposed method as it has been possible to test the network device computed model with a traffic pattern totally unrelated to the training data-set. This test could lead to two conclusions:

- 1) The prediction error could have been too large and a new long training period would have been needed;
- 2) The prediction error could be comparable to the prediction of the previous model and therefore there would be no need for further updates.

The final result is halfway between the two expectations. In fact, on a test of 846 samples

(about 3 days) with new setup data and the same model used for prediction in Figure 4.4, excellent results has been already obtained for Received and Transmitted packets (5% and 7.1% of NRMSE respectively) and sufficient results for the Voip (12% of NRMSE). Figure 4.5 shows the prediction error for $N = 1$ for different models. The case just specified is the one with the null abscissa, that is the model trained with the old setup data. For the abscissa equal to 1 we have an update of the old model with 1 day of new data (about 288 samples). For the abscissa equal to 2 there is an update of the old model with 2 days of new data and so on for the other values up to 9 updates. As can be seen from the error trend compared to the model updates, very low prediction errors has been obtained already after adding a day of data to the initial model. This very important result indicates how it is possible to adapt the predictive model for a network device. Furthermore, combining the results of Chapter 3 it is evident that this technique would allow an optimal control of the device, guaranteeing QoS without the need to increase the characteristics of the network hardware.

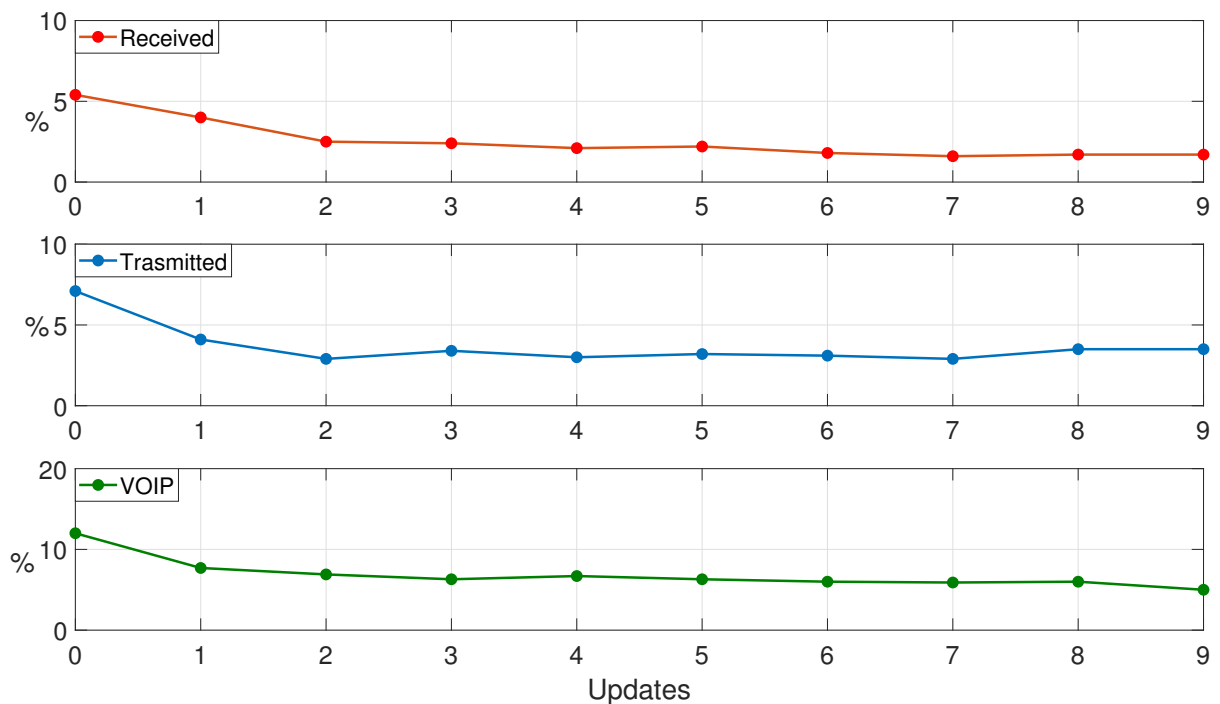


Figure 4.5: NRMSE of the packets predictive model at prediction horizon of $N=1$ with different updated models. Every update add 288 samples (about 1 day) to the previous model training data.

Conclusion

In this work a new methodology to derive accurate models for priority queueing in Software Defined Networks, in order to enable the application of advanced optimization techniques such as MPC, has been developed and validated over the Mininet network emulator framework and over a dedicated hardware network. The obtained results validate the prediction accuracy both of the incoming traffic and of the input/output behavior of a switch device in a SDN-based network. They also provide promising insights on the potential impact of predictive models combined with MPC in terms of packet losses reduction and bandwidth savings. Furthermore, it has been shown that this method obtains excellent prediction results on data coming from a real network of an Italian internet provider (Sonicatel s.r.l.), proving that the proposed control would be very useful to current communications networks to guarantee the required QoS. In future work it has been planned to validate the proposed controller over real network devices, instead of using Mininet.

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Appendix A

Python Codes for Mininet Environment

A.1 main_controller_TOS.py

```
1 from ryu.base import app_manager
2 from ryu.controller import ofp_event
3 from ryu.controller.handler import CONFIG_DISPATCHER, MAIN_DISPATCHER
4 from ryu.controller.handler import set_ev_cls
5 from ryu.ofproto import ofproto_v1_3
6 from qos_simple_switch_13 import *
7 from datapath_monitor_TOS import *
8 from ryu.lib.packet import arp
9 from ryu.lib.packet.arp import ARP_REQUEST, ARP_REPLY
10 from ryu.lib.packet import ipv4
11
12
13 class MainControllerMonitor(app_manager.RyuApp):
14     OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]
15
16     def __init__(self, *args, **kwargs):
17         super(MainControllerMonitor, self).__init__(*args, **kwargs)
18         self.device_behaviour = SimpleSwitch13(*args, **kwargs)
19         self.datapath_id_list = []
20         self.mac_to_port = {}
21         STEP = 300
22         args = {
23             "step":STEP,
24             "logger":self.logger,
25             "dp":self.datapath_id_list
26         }
27         self.monitor = DatapathMonitor(args)
28         self.monitor.start()
29
30     @set_ev_cls(ofp_event.EventOFPSwitchFeatures, CONFIG_DISPATCHER)
31     def switch_feature_handler(self, ev):
32         self.device_behaviour.switch_features_handler(ev)
33         datapath = ev.msg.datapath
34         if datapath not in self.datapath_id_list:
35             self.datapath_id_list.append(datapath)
```

```

36         self.monitor.update(self.datapath_id_list)
37
38     @set_ev_cls(ofp_event.EventOFPPacketIn, MAIN_DISPATCHER)
39     def _packet_in_handler(self, ev):
40         self.device_behaviour._packet_in_handler(ev)
41
42     @set_ev_cls(ofp_event.EventOFPPDescStatsReply, MAIN_DISPATCHER)
43     def desc_stat_reply_handler(self, ev):
44         self.monitor.desc_reply(ev)

```

A.2 datapath_monitor_TOS.py

```

1  from ryu.controller import ofp_event
2  from ryu.controller.handler import CONFIG_DISPATCHER, MAIN_DISPATCHER
3  from ryu.ofproto import ofproto_v1_3
4  from ryu.lib.packet import packet
5  from ryu.lib.packet import ethernet
6  from ryu.lib.packet import ether_types
7  from operator import attrgetter
8  import threading
9  import time
10 import datetime
11
12 import subprocess
13 import json
14 import sys
15
16 from Controller_commands import *
17 import numpy as np
18
19 from subprocess import call
20 import random
21 import os
22
23 now=datetime.datetime.now()
24 year=str(now.year)
25 month=str(now.month)
26 day=str(now.day)
27 date=year+"-"+month+"-"+day+"_"
28 computername="jedi"
29 dpb_folder="/home/jedi/Dropbox/DataNetworkShared/"
30 file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/
    DataLog/"+date+"flowstat.txt", "a")
31 stringa="time"+"\t"+"datapath"+"\t"+"in-port"+"\t"+"eth-dst"+"\t"+"out-
    port"+"\t"+"packets"+"\t"+"bytes"+"\t"+"ip_dscp"+"\t"+"SET_QUEUE\n"
32 file.write(stringa)
33 file.close()
34
35 file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/
    DataLog/"+date+"queuestat.txt", "a")

```

```

36 stringa="time"+"\\t"+"datapath"+"\\t"+"port_no"+"\\t"+"queue_id"+"\\t"+"
    tx_bytes"+"\\t"+"tx_packets"+"\\t"+"tx_errors"+"\\t"+"duration_sec"+"\\t"
    "+"duration_nsec\\n"
37 file.write(stringa)
38 file.close()
39
40 file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/
    DataLog/"+date+"portstat.txt", "a")
41 stringa="time"+"\\t"+"datapath"+"\\t"+"port"+"\\t"+"rx-pkts"+"\\t"+"rx-bytes
    "+"\\t"+"rx_error"+"\\t"+"tx-pkts"+"\\t"+"tx-bytes"+"\\t"+"tx-error"+"\\t"
    "+"rx-dropped"+"\\t"+"tx-dropped"+"\\t"+"rx-crc-err"+"\\t"+"collisions"
    +"\\n"
42 file.write(stringa)
43 file.close()
44
45 file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/
    DataLog/"+date+"queueconfig.txt", "a")
46 stringa="time"+"\\t"+"datapath"+"\\t"+"queue_id"+"\\t"+"type_of_rule"+"\\t"+"
    "rate\\n"
47 file.write(stringa)
48 file.close()
49
50 f = open(dpb_folder+"FlagData.txt", "w")
51 f.write("0")
52 f.close()
53
54 f = open(dpb_folder+"FlagU.txt", "w")
55 f.write("0")
56 f.close()
57
58 def get_switchis():
59     try:
60         output = subprocess.check_output(
61             "curl -X GET http://localhost:8080/stats/switches",
62             stderr=subprocess.STDOUT,
63             shell=True)
64         output=output[output.find("["):]
65         end_response=output.find("]")
66         list1=list(output)
67         list1[end_response]=','
68         output=''.join(list1)+"]"
69     except:
70         output="No NET"
71     return output
72
73 def save_flow_stat(datapath):
74     datapath_in=datapath
75     mom_datapath= ['0' for i in range(16-len(datapath))]
76     mom_datapath=''.join(mom_datapath)
77     datapath=mom_datapath+datapath
78     try:
79         output = subprocess.check_output(
80             "curl -X GET http://localhost:8080/stats/flow/"+datapath,
81             shell=True)

```

```

82     i=0
83     output = output[output.find("{")+1:]
84     end_response = output.find("}]}")+2
85     list1=list(output)
86     list1[end_response-2]='}'
87     list1[end_response-1]=','
88     output=''.join(list1)
89     while i<end_response:
90         output_i=output[i:]
91         i=i+output[i:].find("},")+2
92         otp = output_i[output_i.find("{"):]
93         otp = otp[0:otp.find("},")+1]
94         otp =eval(otp)
95         data = otp
96         json_str = json.dumps(data)
97         jsonList = json.loads(json_str)
98         if jsonList['priority']!=0 and jsonList['match'].get('
in_port'):
99             porta=str(jsonList['actions'])
100             prc = porta.find('T:')
101             #Check if there is "OUTPUT:" in the string
102             if prc >= 0:
103                 porta=porta[prc+2:]
104                 porta = int(porta[0:porta.find(')')-1])
105                 file = open("/home/"+computername+"/Scrivania/
RyuDatapathMonitor-master/DataLog/"+date+"flowstat.txt","a")
106                 now=datetime.datetime.now()
107                 stringa=str(now)+"\t"+datapath_in+"\t"+str(jsonList[
'match'].get('in_port'))+"\t"+str(jsonList['match'].get('dl_dst'))+"
\t"+str(porta)+"\t"+str(jsonList['packet_count'])+"\t"+str(jsonList[
'byte_count'])+"\t None"+" \t None"+" \n"
108                 file.write(stringa)
109                 file.close()
110                 file = open(dpb_folder+"DataFlow.txt","a")
111                 file.write(stringa)
112                 file.close()
113                 file = open(dpb_folder+"DataFlowPrec.txt","a")
114                 file.write(stringa)
115                 file.close()
116             if jsonList['priority']!=0 and str(jsonList['actions']).find
('UE:')>=0:
117                 SET_QUEUE=str(str(jsonList['actions'])[str(jsonList['
actions']).find('UE:')+3:str(jsonList['actions']).find(',')-1])
118                 file = open("/home/"+computername+"/Scrivania/
RyuDatapathMonitor-master/DataLog/"+date+"flowstat.txt","a")
119                 now=datetime.datetime.now()
120                 stringa=str(now)+"\t"+datapath_in+"\t"+str(jsonList[
'match'].get('in_port'))+"\t"+str(jsonList['match'].get('nw_dst'))+"
\t"+"None"+" \t"+str(jsonList['packet_count'])+"\t"+str(jsonList[
'byte_count'])+"\t"+str(jsonList['match'].get('ip_dscp'))+"\t"+
SET_QUEUE+"\n"
121                 file.write(stringa)
122                 file.close()
123                 file = open(dpb_folder+"DataFlow.txt","a")

```

```

124         file.write(stringa)
125         file.close()
126         file = open(dpb_folder+"DataFlowPrec.txt", "a")
127         file.write(stringa)
128         file.close()
129
130     except:
131         print "FlowStat: No NET"
132
133 def save_port_stat(datapath):
134     datapath_in=datapath
135     mom_datapath= ['0' for i in range(16-len(datapath))]
136     mom_datapath=''.join(mom_datapath)
137     datapath=mom_datapath+datapath
138     try:
139         output = subprocess.check_output(
140             "curl -X GET http://localhost:8080/stats/port/"+datapath ,
141             shell=True)
142         i=0
143         output = output[output.find("{")+1:]
144         end_response = output.find("}]}")+2
145         list1=list(output)
146         list1[end_response-2]='}'
147         list1[end_response-1]=','
148         output=''.join(list1)
149         while i<end_response:
150             output_i=output[i:]
151             i=i+output[i:].find("},")+2
152             otp = output_i[output_i.find("{"): ]
153             otp = otp[0:otp.find("},")+1]
154             otp =eval(otp)
155             data = otp
156             json_str = json.dumps(data)
157             jsonList = json.loads(json_str)
158             if jsonList[ 'port_no' ]!="LOCAL":
159                 file = open("/home/"+computername+"/Scrivania/
RyuDatapathMonitor-master/DataLog/"+date+"portstat.txt", "a")
160                 now=datetime.datetime.now()
161                 stringa=str(now)+"\t"+datapath_in+"\t"+str(jsonList[ '
port_no' ])+"\t"+str(jsonList[ 'rx_packets' ])+"\t"+str(jsonList[ '
rx_bytes' ])+"\t"+str(jsonList[ 'rx_errors' ])+"\t"+str(jsonList[ '
tx_packets' ])+"\t"+str(jsonList[ 'tx_bytes' ])+"\t"+str(jsonList[ '
tx_errors' ])+"\t"+str(jsonList[ 'rx_dropped' ])+"\t"+str(jsonList[ '
tx_dropped' ])+"\t"+str(jsonList[ 'rx_crc_err' ])+"\t"+str(jsonList[ '
collisions' ])+"\n"
162                 file.write(stringa)
163                 file.close()
164                 file = open(dpb_folder+"DataPort.txt", "a")
165                 file.write(stringa)
166                 file.close()
167                 file = open(dpb_folder+"DataPortPrec.txt", "a")
168                 file.write(stringa)
169                 file.close()
170

```

```

171     except:
172         print "PortStat: No NET"
173
174 def save_queue_stat(datapath):
175     datapath_in=datapath
176     mom_datapath= ['0' for i in range(16-len(datapath))]
177     mom_datapath=''.join(mom_datapath)
178     datapath=mom_datapath+datapath
179     try:
180         output = subprocess.check_output(
181             "curl -X GET http://localhost:8080/qos/queue/status/"+
datapath ,
182             shell=True)
183         i=0
184         output = output[output.find("ult")+1:]
185         output = output[output.find("{")+1:]
186         end_response = output.find("}}")+2
187         list1=list(output)
188         list1[end_response-2]='}'
189         list1[end_response-1]=','
190         output=''.join(list1)
191         if output[output.find(":")+2:output.find(":")+4]!="[]":
192             while i<end_response:
193                 output_i=output[i:]
194                 i=i+output[i:].find("},")+2
195                 otp = output_i[output_i.find("{"):]
196                 otp = otp[0:otp.find("},")+1]
197                 otp = eval(otp)
198                 data = otp
199                 json_str = json.dumps(data)
200                 jsonList = json.loads(json_str)
201                 file = open("/home/"+computername+"/Scrivania/
RyuDatapathMonitor-master/DataLog/"+date+"queuestat.txt", "a")
202                 now=datetime.datetime.now()
203                 stringa=str(now)+"\t"+datapath_in+"\t"+str(jsonList[ '
port_no ' ])+"\t"+str(jsonList[ 'queue_id ' ])+"\t"+str(jsonList[ '
tx_bytes ' ])+"\t"+str(jsonList[ 'tx_packets ' ])+"\t"+str(jsonList[ '
tx_errors ' ])+"\t"+str(jsonList[ 'duration_sec ' ])+"\t"+str(jsonList[ '
duration_nsec ' ])+"\n"
204                 file.write(stringa)
205                 file.close()
206                 file = open(dpb_folder+"DataQueueStat.txt", "a")
207                 file.write(stringa)
208                 file.close()
209                 file = open(dpb_folder+"DataQueueStatPrec.txt", "a")
210                 file.write(stringa)
211                 file.close()
212
213     except:
214         print "QueueStat: No NET"
215
216 def save_queue_config(datapath):
217     datapath_in=datapath
218     mom_datapath= ['0' for i in range(16-len(datapath))]

```



```

219 mom_datapath=' '.join(mom_datapath)
220 datapath=mom_datapath+datapath
221 try:
222     output = subprocess.check_output(
223         "curl -X GET http://localhost:8080/qos/queue/" + datapath ,
224         shell=True)
225     i=0
226     output=output[1:len(output)-1]
227     jsonList = json.loads(output)
228     config = jsonList['command_result'].get('details')
229     for queue in config:
230         if queue=='2':
231             rate = jsonList['command_result'].get('details').get(
queue).get('config').get('min-rate')
232             type_of_rule='min_rate'
233         else:
234             rate = jsonList['command_result'].get('details').get(
queue).get('config').get('max-rate')
235             type_of_rule='max_rate'
236             file = open("/home/"+computername+"/Scrivania/
RyuDatapathMonitor-master/DataLog/" + date + "queueconfig.txt", "a")
237             now=datetime.datetime.now()
238             stringa=str(now)+"\t"+datapath_in+"\t"+str(queue)+"\t"+str(
type_of_rule)+"\t"+str(rate)+"\n"
239             file.write(stringa)
240             file.close()
241             file = open(dpb_folder+"DataQueueConfig.txt", "a")
242             file.write(stringa)
243             file.close()
244             file = open(dpb_folder+"DataQueueConfigPrec.txt", "a")
245             file.write(stringa)
246             file.close()
247
248     except:
249         print "QueueConfig: No NET"
250
251 class DatapathMonitor():
252     OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]
253
254     def __init__(self, args):
255         self.datapath_list = args["dp"]
256
257         self.monitor = threading.Thread(target=self.
switch_monitor_thread)
258         self.delta = args["step"]
259         self.logger = args["logger"]
260
261         self.started = False
262
263     def start(self):
264         self.monitor.start()
265         self.started = True
266
267     def update(self, dplist):

```

```

268     self.datapath_list = dplist
269
270 def switch_monitor_thread( self ):
271     max_rate_queue=100#Mps
272     max_rate_queue=max_rate_queue*1000000
273     minute_wait=20
274     Time_queue=minute_wait*60
275     Change_flag=Time_queue/ self . delta
276     counter=Change_flag
277     c_q2=0
278     c_q1=1
279     c_q0=1
280     q2=np. arange( 70, 101, 10)*1000000
281     q1=np. arange( 0, 101, 10)*1000000
282     q0=np. arange( 0, 101, 10)*1000000
283
284     print 'Wait for time alignment'
285     wait=self. delta/60
286     check_time=False
287     while check_time==False:
288         now=datetime. datetime. now()
289         if now. minute%wait==0:
290             check_time=True
291         else:
292             time. sleep( 1)
293     print 'Starting Save Data'
294     check_time=False
295     flag=0
296     while True:
297         while check_time==False:
298             now=datetime. datetime. now()
299             if now. minute%wait==0:
300                 check_time=True
301                 print "Save Time: "+str( now)
302             else:
303                 try:
304                     time. sleep( 1)
305                     f = open( dpb_folder+"FlagU. txt", "r")
306                     flag=int( f. read() )
307                 except:
308                     flag=0
309                 try:
310                     if flag==1:#check flag u file
311                         time. sleep( 10)
312                         print( "Change Queues Bw%")
313                         f. close()
314                         #Read new queue BW
315                         i=0
316                         u=[0,0,0]
317                         with open( dpb_folder+"U. txt") as mytxt:
318                             for line in mytxt:
319                                 print ( line)
320                                 u[ i]=int( line)*1000000
321                                 i=i+1

```

```

322         #Set New Queue
323         set_queue("2", "s2-eth2", str(max_rate_queue
), {"\max_rate\ ": \"+str(u[0])+"\"}, {"\max_rate\ ": \"+str(u[1])+"
"\}, {"\min_rate\ ": \"+str(u[2])+"\"})
324         f = open(dpb_folder+"FlagU.txt", "w")
325         f.write("0")
326         f.close()
327
328     else:
329         f.close()
330     except:
331         print("BW File NOT READY")
332 NET=get_switchis()
333 t_sleep = 0.9
334 if NET != "NO NET" and NET!="[, ]":
335     file = open(dpb_folder+"DataFlowPrec.txt", "r")
336     Prec=file.read()
337     file.close()
338     file = open(dpb_folder+"DataFlow.txt", "w")
339     file.write(Prec)
340     file.close()
341     file = open(dpb_folder+"DataFlowPrec.txt", "w")
342     file.close()
343
344     file = open(dpb_folder+"DataPortPrec.txt", "r")
345     Prec=file.read()
346     file.close()
347     file = open(dpb_folder+"DataPort.txt", "w")
348     file.write(Prec)
349     file.close()
350     file = open(dpb_folder+"DataPortPrec.txt", "w")
351     file.close()
352
353     file = open(dpb_folder+"DataQueueStatPrec.txt", "r")
354     Prec=file.read()
355     file.close()
356     file = open(dpb_folder+"DataQueueStat.txt", "w")
357     file.write(Prec)
358     file.close()
359     file = open(dpb_folder+"DataQueueStatPrec.txt", "w")
360     file.close()
361
362     file = open(dpb_folder+"DataQueueConfigPrec.txt", "r")
363     Prec=file.read()
364     file.close()
365     file = open(dpb_folder+"DataQueueConfig.txt", "w")
366     file.write(Prec)
367     file.close()
368     file = open(dpb_folder+"DataQueueConfigPrec.txt", "w")
369     file.close()
370     i=1
371     while i<NET.find(","):
372         mom_NET=NET[i:]
373         datapath=NET[i:i+mom_NET.find(",")]

```

```

374         i=i+mom_NET.find(",")+2
375         save_flow_stat(datapath)
376         save_port_stat(datapath)
377         save_queue_stat(datapath)
378         save_queue_config(datapath)
379         file = open(dpb_folder+"FlagData.txt","w")
380         file.write("1")
381         file.close()
382         while check_time==True:
383             now=datetime.datetime.now()
384             if now.minute%wait!=0:
385                 check_time=False
386             else:
387                 time.sleep(1)
388                 try:
389                     f = open(dpb_folder+"FlagU.txt","r")
390                     flag=int(f.read())
391                 except:
392                     flag=0
393                     continue
394                 try:
395                     if flag==1:#check flag u file
396                         print("Change Queues Bw%")
397                         f.close()
398                         #Read new queue BW
399                         i=0
400                         u=[0,0,0]
401                         with open(dpb_folder+"U.txt") as mytxt:
402                             for line in mytxt:
403                                 print(line)
404                                 u[i]=int(line)*1000000
405                                 i=i+1
406                                 #Set New Queue
407                                 set_queue("2", "s2-eth2", str(
max_rate_queue), "{\max_rate\": \"+str(u[0])+"\"}, {\max_rate\":
\""+str(u[1])+"\"}, {\min_rate\": \"+str(u[2])+"\"}")
408                                 f = open(dpb_folder+"FlagU.txt","w")
409                                 f.write("0")
410                                 f.close()
411                             else:
412                                 f.close()
413                         except:
414                             print("INPUT NOT READY")
415                             continue
416             else:
417                 print "No Network"

```

A.3 Controller_commands.py

```

1 from subprocess import call
2 import threading

```

```

3 import subprocess
4 import random
5 import os
6 import time
7 import json
8 import sys
9
10 def ovssctl_set_bridge(datapath):
11     datapath_in=datapath
12     mom_datapath= ['0' for i in range(16-len(datapath))]
13     mom_datapath=''.join(mom_datapath)
14     datapath=mom_datapath+datapath
15     print "Set ovssctl on switch "+datapath
16     try:
17         os.popen("sudo -S curl -X PUT -d '\`"tcp:127.0.0.1:6632\`"' http
18             ://localhost:8080/v1.0/conf/switches/"+datapath+"/ovssctl_set_bridge", 'w').
19             write("Ao70pa45")
20         print "\n"
21         time.sleep(2)
22     except:
23         print "ovssctl_set_bridge: ERROR"
24
25 def ovssctl_set_bridge(switch_name):
26     print "Set ovssctl on switch "+switch_name
27     try:
28         os.popen("sudo -S ovs-vsctl set Bridge "+switch_name+" protocols
29             =OpenFlow13", 'w').write("Ao70pa45")
30         print "\n"
31     except:
32         print "ovssctl_set_bridge: ERROR"
33
34 def get_switches():
35     print "Get switches id"
36     try:
37         output = subprocess.check_output(
38             "curl -X GET http://localhost:8080/stats/switches",
39             stderr=subprocess.STDOUT,
40             shell=True)
41         output=output[output.find("["):]
42         end_response=output.find("]")
43         list1=list(output)
44         list1[end_response]=','
45         output=''.join(list1)+"]"
46         print "\n"
47     except:
48         output="NO NET"
49     return output
50
51 def switch_ports_name(datapath):
52     datapath_in=datapath
53     mom_datapath= ['0' for i in range(16-len(datapath))]
54     mom_datapath=''.join(mom_datapath)
55     datapath=mom_datapath+datapath
56     print "Get names on switch "+datapath

```

```

54     try:
55         output = subprocess.check_output(
56             "curl -X GET http://localhost:8080/stats/portdesc/" +
datapath ,
57             stderr=subprocess.STDOUT,
58             shell=True)
59         i=0
60         output = output[output.find("{")+1:]
61         end_response = output.find("}]}")+2
62         list1=list(output)
63         list1[end_response-2]='}'
64         list1[end_response-1]=','
65         output=''.join(list1)
66         names = []
67         while i<end_response:
68             output_i=output[i:]
69             i=i+output[i:].find("},")+2
70             otp = output_i[output_i.find("{"):]
71             otp = otp[0:otp.find("},")+1]
72             otp =eval(otp)
73             data = otp
74             json_str = json.dumps(data)
75             jsonList = json.loads(json_str)
76             if jsonList['port_no']=="LOCAL":
77                 names.append(str(jsonList['name']))
78             else:
79                 names.append(str(jsonList['name']))
80         print "\n"
81         return names
82
83
84     except:
85         print "Switch port name: ERROR"
86
87
88 def queue_rule(datapath , port_number , ip_dscp , queue_number):
89     mom_datapath= ['0' for i in range(16-len(datapath))]
90     mom_datapath=''.join(mom_datapath)
91     datapath=mom_datapath+datapath
92     print "Set queue rule on switch "+datapath+" on port "+port_number
93     try:
94         os.popen("curl -X POST -d '{\"match\": {\"ip_dscp\": \"\"+ip_dscp
+\"\"}, \"actions\": {\"queue\": \"\"+queue_number+\"\"}}' http://
localhost:8080/qos/rules/" +datapath , 'w').write("Ao70pa45")
95         time.sleep(0.1)
96         print "\n"
97     except:
98         print "Set queue rule: Error"
99
100 def queue_rule_byIP(datapath , port_number , ip_dscp , queue_number , ip_dst
):
101     mom_datapath= ['0' for i in range(16-len(datapath))]
102     mom_datapath=''.join(mom_datapath)
103     datapath=mom_datapath+datapath

```

```

104     print "Set queue rule on switch "+datapath+" on port "+port_number
105     try:
106         os.popen("curl -X POST -d '{\"match\": {\"nw_dst\": \""+ip_dst+"
    \", \"ip_dscp\": \""+ip_dscp+"\"}, \"actions\": {\"queue\": \""+
queue_number+"\"}}' http://localhost:8080/qos/rules/"+datapath, 'w')
    .write("Ao70pa45")
107         time.sleep(0.1)
108         print "\n"
109     except:
110         print "Set queue rule: Error"
111
112 def set_queue(datapath, port_id, max_rate, queue_rate_list):
113     mom_datapath= ['0' for i in range(16-len(datapath))]
114     mom_datapath=''.join(mom_datapath)
115     datapath=mom_datapath+datapath
116     print "Set queue on port "+port_id+" of switch "+datapath
117     print queue_rate_list
118     try:
119         output = subprocess.check_output("curl -X POST -d '{\"port_name
    \": \""+port_id+"\", \"type\": \"linux-htb\", \"max_rate\": \""+
max_rate+"\", \"queues\": [\""+queue_rate_list+"\"]}' http://localhost
:8080/qos/queue/"+datapath,
120         stderr=subprocess.STDOUT,
121         shell=True)
122         time.sleep(0.1)
123         print "\n"
124     except:
125         print "Set queue: Error"
126
127
128 def set_Telecom_queue(datapath, port_number, IP_flag, IP_dst):
129     port=port_number
130     mom_datapath= ['0' for i in range(16-len(datapath))]
131     mom_datapath=''.join(mom_datapath)
132     datapath=mom_datapath+datapath
133     if IP_flag==True:
134         queue_rule_byIP(datapath, port, "0", "0", IP_dst)#Service 0
135         queue_rule_byIP(datapath, port, "8", "0", IP_dst)#Service 1
136         queue_rule_byIP(datapath, port, "10", "0", IP_dst)#Service 1
137         queue_rule_byIP(datapath, port, "12", "0", IP_dst)#Service 1
138         queue_rule_byIP(datapath, port, "14", "0", IP_dst)#Service 1
139         queue_rule_byIP(datapath, port, "24", "0", IP_dst)#Service 3
140         queue_rule_byIP(datapath, port, "26", "0", IP_dst)#Service 3
141         queue_rule_byIP(datapath, port, "28", "0", IP_dst)#Service 3
142         queue_rule_byIP(datapath, port, "30", "0", IP_dst)#Service 3
143
144         queue_rule_byIP(datapath, port, "16", "1", IP_dst)#Service 2
145         queue_rule_byIP(datapath, port, "18", "1", IP_dst)#Service 2
146         queue_rule_byIP(datapath, port, "20", "1", IP_dst)#Service 2
147         queue_rule_byIP(datapath, port, "22", "1", IP_dst)#Service 2
148         queue_rule_byIP(datapath, port, "32", "1", IP_dst)#Service 4
149         queue_rule_byIP(datapath, port, "34", "1", IP_dst)#Service 4
150         queue_rule_byIP(datapath, port, "36", "1", IP_dst)#Service 4
151         queue_rule_byIP(datapath, port, "38", "1", IP_dst)#Service 4

```

```

152     queue_rule_byIP(datapath , port , "48" , "1" , IP_dst)#Service 6
153     queue_rule_byIP(datapath , port , "56" , "1" , IP_dst)#Service 7
154
155     queue_rule_byIP(datapath , port , "40" , "2" , IP_dst)#Service 5
156     queue_rule_byIP(datapath , port , "46" , "2" , IP_dst)#Service 5
157
158     if IP_flag==False:
159         #Default Queue (queue_id = 0)
160         queue_rule(datapath , port , "0" , "0")#Service 0
161         queue_rule(datapath , port , "8" , "0")#Service 1
162         queue_rule(datapath , port , "10" , "0")#Service 1
163         queue_rule(datapath , port , "12" , "0")#Service 1
164         queue_rule(datapath , port , "14" , "0")#Service 1
165         queue_rule(datapath , port , "24" , "0")#Service 3
166         queue_rule(datapath , port , "26" , "0")#Service 3
167         queue_rule(datapath , port , "28" , "0")#Service 3
168         queue_rule(datapath , port , "30" , "0")#Service 3
169         #Premium Queue (queue_id = 1)
170         queue_rule(datapath , port , "16" , "1")#Service 2
171         queue_rule(datapath , port , "18" , "1")#Service 2
172         queue_rule(datapath , port , "20" , "1")#Service 2
173         queue_rule(datapath , port , "22" , "1")#Service 2
174         queue_rule(datapath , port , "32" , "1")#Service 4
175         queue_rule(datapath , port , "34" , "1")#Service 4
176         queue_rule(datapath , port , "36" , "1")#Service 4
177         queue_rule(datapath , port , "38" , "1")#Service 4
178         queue_rule(datapath , port , "48" , "1")#Service 6
179         queue_rule(datapath , port , "56" , "1")#Service 7
180         #Gold Queue (queue_id = 2)
181         queue_rule(datapath , port , "40" , "2")#Service 5
182         queue_rule(datapath , port , "46" , "2")#Service 5

```

A.4 qos_simple_switch_13.py

```

1 # Copyright (C) 2011 Nippon Telegraph and Telephone Corporation.
2 #
3 # Licensed under the Apache License, Version 2.0 (the "License");
4 # you may not use this file except in compliance with the License.
5 # You may obtain a copy of the License at
6 #
7 #     http://www.apache.org/licenses/LICENSE-2.0
8 #
9 # Unless required by applicable law or agreed to in writing, software
10 # distributed under the License is distributed on an "AS IS" BASIS,
11 # WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or
12 # implied.
13 # See the License for the specific language governing permissions and
14 # limitations under the License.
15
16 from ryu.base import app_manager
17 from ryu.controller import ofp_event

```



```

18 from ryu.controller.handler import CONFIG_DISPATCHER, MAIN_DISPATCHER
19 from ryu.controller.handler import set_ev_cls
20 from ryu.ofproto import ofproto_v1_3
21 from ryu.lib.packet import packet
22 from ryu.lib.packet import ethernet
23 from ryu.lib.packet import ether_types
24
25 import subprocess
26
27
28 class SimpleSwitch13(app_manager.RyuApp):
29     OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]
30
31     def __init__(self, *args, **kwargs):
32         super(SimpleSwitch13, self).__init__(*args, **kwargs)
33         self.mac_to_port = {}
34
35     @set_ev_cls(ofp_event.EventOFPSwitchFeatures, CONFIG_DISPATCHER)
36     def switch_features_handler(self, ev):
37         datapath = ev.msg.datapath
38         ofproto = datapath.ofproto
39         parser = datapath.ofproto_parser
40
41         # install table-miss flow entry
42         #
43         # We specify NO BUFFER to max_len of the output action due to
44         # OVS bug. At this moment, if we specify a lesser number, e.g.,
45         # 128, OVS will send Packet-In with invalid buffer_id and
46         # truncated packet data. In that case, we cannot output packets
47         # correctly. The bug has been fixed in OVS v2.1.0.
48         match = parser.OFPMatch()
49         actions = [parser.OFPActionOutput(ofproto.OFPP_CONTROLLER,
50                                         ofproto.OFPCML_NO_BUFFER)]
51         self.add_flow(datapath, 0, match, actions)
52
53     def add_flow(self, datapath, priority, match, actions, buffer_id=
54 None):
55         ofproto = datapath.ofproto
56         parser = datapath.ofproto_parser
57
58         inst = [parser.OFPInstructionActions(ofproto.OFPIT_APPLY_ACTIONS
59 ,
60                                         actions)]
61
62         if buffer_id:
63             mod = parser.OFPFlowMod(datapath=datapath, buffer_id=
64 buffer_id,
65                                     priority=priority, match=match,
66                                     instructions=inst, table_id=1)
67         else:
68             mod = parser.OFPFlowMod(datapath=datapath, priority=priority
69 ,
70                                     match=match, instructions=inst,
71                                     table_id=1)
72         datapath.send_msg(mod)

```

```

67
68 @set_ev_cls(ofp_event.EventOFPPacketIn, MAIN_DISPATCHER)
69 def _packet_in_handler(self, ev):
70     # If you hit this you might want to increase
71     # the "miss_send_length" of your switch
72     if ev.msg.msg_len < ev.msg.total_len:
73         self.logger.debug("packet truncated: only %s of %s bytes",
74                             ev.msg.msg_len, ev.msg.total_len)
75
76     msg = ev.msg
77     datapath = msg.datapath
78     ofproto = datapath.ofproto
79     parser = datapath.ofproto_parser
80     in_port = msg.match['in_port']
81
82     pkt = packet.Packet(msg.data)
83     eth = pkt.get_protocols(ethernet.ethernet)[0]
84
85     if eth.ethertype == ether_types.ETH_TYPE_LLDP:
86         # ignore lldp packet
87         return
88     dst = eth.dst
89     src = eth.src
90
91     dpid = datapath.id
92     self.mac_to_port.setdefault(dpid, {})
93
94     # learn a mac address to avoid FLOOD next time.
95     self.mac_to_port[dpid][src] = in_port
96
97     if dst in self.mac_to_port[dpid]:
98         out_port = self.mac_to_port[dpid][dst]
99     else:
100         out_port = ofproto.OFPP_FLOOD
101
102     actions = [parser.OFPActionOutput(out_port)]
103
104     # install a flow to avoid packet_in next time
105     if out_port != ofproto.OFPP_FLOOD:
106         match = parser.OFPMatch(in_port=in_port, eth_dst=dst,
107                                 eth_src=src)
108         # verify if we have a valid buffer_id, if yes avoid to send
109         both
110         # flow_mod & packet_out
111         if msg.buffer_id != ofproto.OFP_NO_BUFFER:
112             self.add_flow(datapath, 1, match, actions, msg.buffer_id
113                             )
114         else:
115             self.add_flow(datapath, 1, match, actions)
116         data = None
117     if msg.buffer_id == ofproto.OFP_NO_BUFFER:
118         data = msg.data

```

```

117         out = parser.OFPPacketOut(datapath=datapath, buffer_id=msg.
118         buffer_id,
119         datapath.send_msg(out)
118         in_port=in_port, actions=actions, data
119         =data)

```

A.5 ofctl_rest.py

```

1 # Copyright (C) 2012 Nippon Telegraph and Telephone Corporation.
2 #
3 # Licensed under the Apache License, Version 2.0 (the "License");
4 # you may not use this file except in compliance with the License.
5 # You may obtain a copy of the License at
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7 # http://www.apache.org/licenses/LICENSE-2.0
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9 # Unless required by applicable law or agreed to in writing, software
10 # distributed under the License is distributed on an "AS IS" BASIS,
11 # WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or
12 # implied.
13 # See the License for the specific language governing permissions and
14 # limitations under the License.
15
16 import logging
17 import json
18 import ast
19
20 from ryu.base import app_manager
21 from ryu.controller import ofp_event
22 from ryu.controller import dpset
23 from ryu.controller.handler import MAIN_DISPATCHER
24 from ryu.controller.handler import set_ev_cls
25 from ryu.exception import RyuException
26 from ryu.ofproto import ofproto_v1_0
27 from ryu.ofproto import ofproto_v1_2
28 from ryu.ofproto import ofproto_v1_3
29 from ryu.ofproto import ofproto_v1_4
30 from ryu.ofproto import ofproto_v1_5
31 from ryu.lib import ofctl_v1_0
32 from ryu.lib import ofctl_v1_2
33 from ryu.lib import ofctl_v1_3
34 from ryu.lib import ofctl_v1_4
35 from ryu.lib import ofctl_v1_5
36 from ryu.app.wsgi import ControllerBase
37 from ryu.app.wsgi import Response
38 from ryu.app.wsgi import WSGIApplication
39
40 LOG = logging.getLogger('ryu.app.ofctl_rest')
41
42 # supported ofctl versions in this restful app
43 supported_ofctl = {

```

```

44     ofproto_v1_0.OFP_VERSION: ofctl_v1_0 ,
45     ofproto_v1_2.OFP_VERSION: ofctl_v1_2 ,
46     ofproto_v1_3.OFP_VERSION: ofctl_v1_3 ,
47     ofproto_v1_4.OFP_VERSION: ofctl_v1_4 ,
48     ofproto_v1_5.OFP_VERSION: ofctl_v1_5 ,
49 }
50
51 # REST API
52 #
53
54 # Retrieve the switch stats
55 #
56 # get the list of all switches
57 # GET /stats/switches
58 #
59 # get the desc stats of the switch
60 # GET /stats/desc/<dpid>
61 #
62 # get flows desc stats of the switch
63 # GET /stats/flowdesc/<dpid>
64 #
65 # get flows desc stats of the switch filtered by the fields
66 # POST /stats/flowdesc/<dpid>
67 #
68 # get flows stats of the switch
69 # GET /stats/flow/<dpid>
70 #
71 # get flows stats of the switch filtered by the fields
72 # POST /stats/flow/<dpid>
73 #
74 # get aggregate flows stats of the switch
75 # GET /stats/aggregateflow/<dpid>
76 #
77 # get aggregate flows stats of the switch filtered by the fields
78 # POST /stats/aggregateflow/<dpid>
79 #
80 # get table stats of the switch
81 # GET /stats/table/<dpid>
82 #
83 # get table features stats of the switch
84 # GET /stats/tablefeatures/<dpid>
85 #
86 # get ports stats of the switch
87 # GET /stats/port/<dpid>[/<port>]
88 # Note: Specification of port number is optional
89 #
90 # get queues stats of the switch
91 # GET /stats/queue/<dpid>[/<port>[/<queue_id>]]
92 # Note: Specification of port number and queue id are optional
93 #     If you want to omitting the port number and setting the queue id
94 #     ,
95 #     please specify the keyword "ALL" to the port number
96 #     e.g. GET /stats/queue/1/ALL/1

```

```

97 # get queues config stats of the switch
98 # GET /stats/queueconfig/<dpid>[/<port>]
99 # Note: Specification of port number is optional
100 #
101 # get queues desc stats of the switch
102 # GET /stats/queuedesc/<dpid>[/<port>[/<queue_id>]]
103 # Note: Specification of port number and queue id are optional
104 #     If you want to omitting the port number and setting the queue id
105 #     ,
106 #     please specify the keyword "ALL" to the port number
107 #     e.g. GET /stats/queuedesc/1/ALL/1
108 #
109 # get meter features stats of the switch
110 # GET /stats/meterfeatures/<dpid>
111 #
112 # get meter config stats of the switch
113 # GET /stats/meterconfig/<dpid>[/<meter_id>]
114 # Note: Specification of meter id is optional
115 #
116 # get meter desc stats of the switch
117 # GET /stats/meterdesc/<dpid>[/<meter_id>]
118 # Note: Specification of meter id is optional
119 #
120 # get meters stats of the switch
121 # GET /stats/meter/<dpid>[/<meter_id>]
122 # Note: Specification of meter id is optional
123 #
124 # get group features stats of the switch
125 # GET /stats/groupfeatures/<dpid>
126 #
127 # get groups desc stats of the switch
128 # GET /stats/groupdesc/<dpid>[/<group_id>]
129 # Note: Specification of group id is optional (OpenFlow 1.5 or later)
130 #
131 # get groups stats of the switch
132 # GET /stats/group/<dpid>[/<group_id>]
133 # Note: Specification of group id is optional
134 #
135 # get ports description of the switch
136 # GET /stats/portdesc/<dpid>[/<port_no>]
137 # Note: Specification of port number is optional (OpenFlow 1.5 or later)
138 #
139 # Update the switch stats
140 #
141 # add a flow entry
142 # POST /stats/flowentry/add
143 #
144 # modify all matching flow entries
145 # POST /stats/flowentry/modify
146 #
147 # modify flow entry strictly matching wildcards and priority
148 # POST /stats/flowentry/modify_strict
149 #
150 # delete all matching flow entries

```

```

150 # POST /stats/flowentry/delete
151 #
152 # delete flow entry strictly matching wildcards and priority
153 # POST /stats/flowentry/delete_strict
154 #
155 # delete all flow entries of the switch
156 # DELETE /stats/flowentry/clear/<dpid>
157 #
158 # add a meter entry
159 # POST /stats/meterentry/add
160 #
161 # modify a meter entry
162 # POST /stats/meterentry/modify
163 #
164 # delete a meter entry
165 # POST /stats/meterentry/delete
166 #
167 # add a group entry
168 # POST /stats/grouppentry/add
169 #
170 # modify a group entry
171 # POST /stats/grouppentry/modify
172 #
173 # delete a group entry
174 # POST /stats/grouppentry/delete
175 #
176 # modify behavior of the physical port
177 # POST /stats/portdesc/modify
178 #
179 # modify role of controller
180 # POST /stats/role
181 #
182 #
183 # send a experimeter message
184 # POST /stats/experimenter/<dpid>
185
186
187 class CommandNotFoundError(RyuException):
188     message = 'No such command : %(cmd)s'
189
190
191 class PortNotFoundError(RyuException):
192     message = 'No such port info: %(port_no)s'
193
194
195 def stats_method(method):
196     def wrapper(self, req, dpid, *args, **kwargs):
197         # Get datapath instance from DPSet
198         try:
199             dp = self.dpset.get(int(str(dpid)), 0)
200         except ValueError:
201             LOG.exception('Invalid dpid: %s', dpid)
202             return Response(status=400)
203         if dp is None:

```

```

204         LOG.error('No such Datapath: %s', dpid)
205         return Response(status=404)
206
207     # Get lib/ofctl_* module
208     try:
209         ofctl = supported_ofctl.get(dp.ofproto.OFP_VERSION)
210     except KeyError:
211         LOG.exception('Unsupported OF version: %s',
212                       dp.ofproto.OFP_VERSION)
213         return Response(status=501)
214
215     # Invoke StatsController method
216     try:
217         ret = method(self, req, dp, ofctl, *args, **kwargs)
218         return Response(content_type='application/json',
219                        body=json.dumps(ret))
220     except ValueError:
221         LOG.exception('Invalid syntax: %s', req.body)
222         return Response(status=400)
223     except AttributeError:
224         LOG.exception('Unsupported OF request in this version: %s',
225                       dp.ofproto.OFP_VERSION)
226         return Response(status=501)
227
228     return wrapper
229
230
231 def command_method(method):
232     def wrapper(self, req, *args, **kwargs):
233         # Parse request json body
234         try:
235             if req.body:
236                 # We use ast.literal_eval() to parse request json body
237                 # instead of json.loads().
238                 # Because we need to parse binary format body
239                 # in send_experimenter().
240                 body = ast.literal_eval(req.body.decode('utf-8'))
241             else:
242                 body = {}
243         except SyntaxError:
244             LOG.exception('Invalid syntax: %s', req.body)
245             return Response(status=400)
246
247         # Get datapath_id from request parameters
248         dpid = body.get('dpid', None)
249         if not dpid:
250             try:
251                 dpid = kwargs.pop('dpid')
252             except KeyError:
253                 LOG.exception('Cannot get dpid from request parameters')
254                 return Response(status=400)
255
256         # Get datapath instance from DPSet
257         try:

```

```

258         dp = self.dpset.get(int(str(dpid), 0))
259     except ValueError:
260         LOG.exception('Invalid dpid: %s', dpid)
261         return Response(status=400)
262     if dp is None:
263         LOG.error('No such Datapath: %s', dpid)
264         return Response(status=404)
265
266     # Get lib/ofctl_* module
267     try:
268         ofctl = supported_ofctl.get(dp.ofproto.OFP_VERSION)
269     except KeyError:
270         LOG.exception('Unsupported OF version: version=%s',
271                       dp.ofproto.OFP_VERSION)
272         return Response(status=501)
273
274     # Invoke StatsController method
275     try:
276         method(self, req, dp, ofctl, body, *args, **kwargs)
277         return Response(status=200)
278     except ValueError:
279         LOG.exception('Invalid syntax: %s', req.body)
280         return Response(status=400)
281     except AttributeError:
282         LOG.exception('Unsupported OF request in this version: %s',
283                       dp.ofproto.OFP_VERSION)
284         return Response(status=501)
285     except CommandNotFoundError as e:
286         LOG.exception(e.message)
287         return Response(status=404)
288     except PortNotFoundError as e:
289         LOG.exception(e.message)
290         return Response(status=404)
291
292     return wrapper
293
294
295 class StatsController(ControllerBase):
296     def __init__(self, req, link, data, **config):
297         super(StatsController, self).__init__(req, link, data, **config)
298         self.dpset = data['dpset']
299         self.waiters = data['waiters']
300
301     def get_dpids(self, req, **_kwargs):
302         dps = list(self.dpset.dps.keys())
303         body = json.dumps(dps)
304         return Response(content_type='application/json', body=body)
305
306     @stats_method
307     def get_desc_stats(self, req, dp, ofctl, **kwargs):
308         return ofctl.get_desc_stats(dp, self.waiters)
309
310     @stats_method
311     def get_flow_desc(self, req, dp, ofctl, **kwargs):

```



```

312         flow = req.json if req.body else {}
313         return ofctl.get_flow_desc(dp, self.waiters, flow)
314
315     @stats_method
316     def get_flow_stats(self, req, dp, ofctl, **kwargs):
317         flow = req.json if req.body else {}
318         return ofctl.get_flow_stats(dp, self.waiters, flow)
319
320     @stats_method
321     def get_aggregate_flow_stats(self, req, dp, ofctl, **kwargs):
322         flow = req.json if req.body else {}
323         return ofctl.get_aggregate_flow_stats(dp, self.waiters, flow)
324
325     @stats_method
326     def get_table_stats(self, req, dp, ofctl, **kwargs):
327         return ofctl.get_table_stats(dp, self.waiters)
328
329     @stats_method
330     def get_table_features(self, req, dp, ofctl, **kwargs):
331         return ofctl.get_table_features(dp, self.waiters)
332
333     @stats_method
334     def get_port_stats(self, req, dp, ofctl, port=None, **kwargs):
335         if port == "ALL":
336             port = None
337
338         return ofctl.get_port_stats(dp, self.waiters, port)
339
340     @stats_method
341     def get_queue_stats(self, req, dp, ofctl,
342                        port=None, queue_id=None, **kwargs):
343         if port == "ALL":
344             port = None
345
346         if queue_id == "ALL":
347             queue_id = None
348
349         return ofctl.get_queue_stats(dp, self.waiters, port, queue_id)
350
351     @stats_method
352     def get_queue_config(self, req, dp, ofctl, port=None, **kwargs):
353         if port == "ALL":
354             port = None
355
356         return ofctl.get_queue_config(dp, self.waiters, port)
357
358     @stats_method
359     def get_queue_desc(self, req, dp, ofctl,
360                      port=None, queue=None, **kwargs):
361         if port == "ALL":
362             port = None
363
364         if queue == "ALL":
365             queue = None

```

```

366         return ofctl.get_queue_desc(dp, self.waiters, port, queue)
367
368
369     @stats_method
370     def get_meter_features(self, req, dp, ofctl, **kwargs):
371         return ofctl.get_meter_features(dp, self.waiters)
372
373     @stats_method
374     def get_meter_config(self, req, dp, ofctl, meter_id=None, **kwargs):
375         if meter_id == "ALL":
376             meter_id = None
377
378         return ofctl.get_meter_config(dp, self.waiters, meter_id)
379
380     @stats_method
381     def get_meter_desc(self, req, dp, ofctl, meter_id=None, **kwargs):
382         if meter_id == "ALL":
383             meter_id = None
384
385         return ofctl.get_meter_desc(dp, self.waiters, meter_id)
386
387     @stats_method
388     def get_meter_stats(self, req, dp, ofctl, meter_id=None, **kwargs):
389         if meter_id == "ALL":
390             meter_id = None
391
392         return ofctl.get_meter_stats(dp, self.waiters, meter_id)
393
394     @stats_method
395     def get_group_features(self, req, dp, ofctl, **kwargs):
396         return ofctl.get_group_features(dp, self.waiters)
397
398     @stats_method
399     def get_group_desc(self, req, dp, ofctl, group_id=None, **kwargs):
400         if dp.ofproto.OFP_VERSION < ofproto_v1_5.OFP_VERSION:
401             return ofctl.get_group_desc(dp, self.waiters)
402         else:
403             return ofctl.get_group_desc(dp, self.waiters, group_id)
404
405     @stats_method
406     def get_group_stats(self, req, dp, ofctl, group_id=None, **kwargs):
407         if group_id == "ALL":
408             group_id = None
409
410         return ofctl.get_group_stats(dp, self.waiters, group_id)
411
412     @stats_method
413     def get_port_desc(self, req, dp, ofctl, port_no=None, **kwargs):
414         if dp.ofproto.OFP_VERSION < ofproto_v1_5.OFP_VERSION:
415             return ofctl.get_port_desc(dp, self.waiters)
416         else:
417             return ofctl.get_port_desc(dp, self.waiters, port_no)
418
419     @stats_method

```

```

420 def get_role(self, req, dp, ofctl, **kwargs):
421     return ofctl.get_role(dp, self.waiters)
422
423 @command_method
424 def mod_flow_entry(self, req, dp, ofctl, flow, cmd, **kwargs):
425     cmd_convert = {
426         'add': dp.ofproto.OFPFC_ADD,
427         'modify': dp.ofproto.OFPFC_MODIFY,
428         'modify_strict': dp.ofproto.OFPFC_MODIFY_STRICT,
429         'delete': dp.ofproto.OFPFC_DELETE,
430         'delete_strict': dp.ofproto.OFPFC_DELETE_STRICT,
431     }
432     mod_cmd = cmd_convert.get(cmd, None)
433     if mod_cmd is None:
434         raise CommandNotFoundError(cmd=cmd)
435
436     ofctl.mod_flow_entry(dp, flow, mod_cmd)
437
438 @command_method
439 def delete_flow_entry(self, req, dp, ofctl, flow, **kwargs):
440     if ofproto_v1_0.OFP_VERSION == dp.ofproto.OFP_VERSION:
441         flow = {}
442     else:
443         flow = {'table_id': dp.ofproto.OFPTT_ALL}
444
445     ofctl.mod_flow_entry(dp, flow, dp.ofproto.OFPFC_DELETE)
446
447 @command_method
448 def mod_meter_entry(self, req, dp, ofctl, meter, cmd, **kwargs):
449     cmd_convert = {
450         'add': dp.ofproto.OFPMC_ADD,
451         'modify': dp.ofproto.OFPMC_MODIFY,
452         'delete': dp.ofproto.OFPMC_DELETE,
453     }
454     mod_cmd = cmd_convert.get(cmd, None)
455     if mod_cmd is None:
456         raise CommandNotFoundError(cmd=cmd)
457
458     ofctl.mod_meter_entry(dp, meter, mod_cmd)
459
460 @command_method
461 def mod_group_entry(self, req, dp, ofctl, group, cmd, **kwargs):
462     cmd_convert = {
463         'add': dp.ofproto.OFPGC_ADD,
464         'modify': dp.ofproto.OFPGC_MODIFY,
465         'delete': dp.ofproto.OFPGC_DELETE,
466     }
467     mod_cmd = cmd_convert.get(cmd, None)
468     if mod_cmd is None:
469         raise CommandNotFoundError(cmd=cmd)
470
471     ofctl.mod_group_entry(dp, group, mod_cmd)
472
473 @command_method

```

```

474     def mod_port_behavior(self, req, dp, ofctl, port_config, cmd, **
475     kwargs):
476         port_no = port_config.get('port_no', None)
477         port_no = int(str(port_no), 0)
478
479         port_info = self.dpset.port_state[int(dp.id)].get(port_no)
480         if port_info:
481             port_config.setdefault('hw_addr', port_info.hw_addr)
482             if dp.ofproto.OFP_VERSION < ofproto_v1_4.OFP_VERSION:
483                 port_config.setdefault('advertise', port_info.advertised
484 )
485             else:
486                 port_config.setdefault('properties', port_info.
487 properties)
488             else:
489                 raise PortNotFoundError(port_no=port_no)
490
491             if cmd != 'modify':
492                 raise CommandNotFoundError(cmd=cmd)
493
494             ofctl.mod_port_behavior(dp, port_config)
495
496 @command_method
497 def send_experimenter(self, req, dp, ofctl, exp, **kwargs):
498     ofctl.send_experimenter(dp, exp)
499
500 @command_method
501 def set_role(self, req, dp, ofctl, role, **kwargs):
502     ofctl.set_role(dp, role)
503
504 class RestStatsApi(app_manager.RyuApp):
505     OFP_VERSIONS = [ofproto_v1_0.OFP_VERSION,
506                    ofproto_v1_2.OFP_VERSION,
507                    ofproto_v1_3.OFP_VERSION,
508                    ofproto_v1_4.OFP_VERSION,
509                    ofproto_v1_5.OFP_VERSION]
510
511     _CONTEXTS = {
512         'dpset': dpset.DPSet,
513         'wsgi': WSGIApplication
514     }
515
516     def __init__(self, *args, **kwargs):
517         super(RestStatsApi, self).__init__(*args, **kwargs)
518         self.dpset = kwargs['dpset']
519         wsgi = kwargs['wsgi']
520         self.waiters = {}
521         self.data = {}
522         self.data['dpset'] = self.dpset
523         self.data['waiters'] = self.waiters
524         mapper = wsgi.mapper
525
526         wsgi.registry['StatsController'] = self.data
527         path = '/stats'

```

```

525     uri = path + '/switches'
526     mapper.connect('stats', uri,
527                    controller=StatsController, action='get_dpids',
528                    conditions=dict(method=['GET']))
529
530     uri = path + '/desc/{dpid}'
531     mapper.connect('stats', uri,
532                    controller=StatsController, action='
533     get_desc_stats',
534                    conditions=dict(method=['GET']))
535
536     uri = path + '/flowdesc/{dpid}'
537     mapper.connect('stats', uri,
538                    controller=StatsController, action='
539     get_flow_stats',
540                    conditions=dict(method=['GET', 'POST']))
541
542     uri = path + '/flow/{dpid}'
543     mapper.connect('stats', uri,
544                    controller=StatsController, action='
545     get_flow_stats',
546                    conditions=dict(method=['GET', 'POST']))
547
548     uri = path + '/aggregateflow/{dpid}'
549     mapper.connect('stats', uri,
550                    controller=StatsController,
551                    action='get_aggregate_flow_stats',
552                    conditions=dict(method=['GET', 'POST']))
553
554     uri = path + '/table/{dpid}'
555     mapper.connect('stats', uri,
556                    controller=StatsController, action='
557     get_table_stats',
558                    conditions=dict(method=['GET']))
559
560     uri = path + '/tablefeatures/{dpid}'
561     mapper.connect('stats', uri,
562                    controller=StatsController, action='
563     get_table_features',
564                    conditions=dict(method=['GET']))
565
566     uri = path + '/port/{dpid}'
567     mapper.connect('stats', uri,
568                    controller=StatsController, action='
569     get_port_stats',
570                    conditions=dict(method=['GET']))
571
572     uri = path + '/port/{dpid}/{port}'
573     mapper.connect('stats', uri,
574                    controller=StatsController, action='
575     get_port_stats',
576                    conditions=dict(method=['GET']))
577
578     uri = path + '/queue/{dpid}'

```

```

572     mapper.connect('stats', uri,
573                   controller=StatsController, action='
get_queue_stats',
574                   conditions=dict(method=['GET']))
575
576     uri = path + '/queue/{dpid}/{port}'
577     mapper.connect('stats', uri,
578                   controller=StatsController, action='
get_queue_stats',
579                   conditions=dict(method=['GET']))
580
581     uri = path + '/queue/{dpid}/{port}/{queue_id}'
582     mapper.connect('stats', uri,
583                   controller=StatsController, action='
get_queue_stats',
584                   conditions=dict(method=['GET']))
585
586     uri = path + '/queueconfig/{dpid}'
587     mapper.connect('stats', uri,
588                   controller=StatsController, action='
get_queue_config',
589                   conditions=dict(method=['GET']))
590
591     uri = path + '/queueconfig/{dpid}/{port}'
592     mapper.connect('stats', uri,
593                   controller=StatsController, action='
get_queue_config',
594                   conditions=dict(method=['GET']))
595
596     uri = path + '/queuedesc/{dpid}'
597     mapper.connect('stats', uri,
598                   controller=StatsController, action='
get_queue_desc',
599                   conditions=dict(method=['GET']))
600
601     uri = path + '/queuedesc/{dpid}/{port}'
602     mapper.connect('stats', uri,
603                   controller=StatsController, action='
get_queue_desc',
604                   conditions=dict(method=['GET']))
605
606     uri = path + '/queuedesc/{dpid}/{port}/{queue}'
607     mapper.connect('stats', uri,
608                   controller=StatsController, action='
get_queue_desc',
609                   conditions=dict(method=['GET']))
610
611     uri = path + '/meterfeatures/{dpid}'
612     mapper.connect('stats', uri,
613                   controller=StatsController, action='
get_meter_features',
614                   conditions=dict(method=['GET']))
615
616     uri = path + '/meterconfig/{dpid}'

```

```

617         mapper.connect('stats', uri,
618                        controller=StatsController, action='
get_meter_config',
619                        conditions=dict(method=['GET']))
620
621         uri = path + '/meterconfig/{dpid}/{meter_id}'
622         mapper.connect('stats', uri,
623                        controller=StatsController, action='
get_meter_config',
624                        conditions=dict(method=['GET']))
625
626         uri = path + '/meterdesc/{dpid}'
627         mapper.connect('stats', uri,
628                        controller=StatsController, action='
get_meter_desc',
629                        conditions=dict(method=['GET']))
630
631         uri = path + '/meterdesc/{dpid}/{meter_id}'
632         mapper.connect('stats', uri,
633                        controller=StatsController, action='
get_meter_desc',
634                        conditions=dict(method=['GET']))
635
636         uri = path + '/meter/{dpid}'
637         mapper.connect('stats', uri,
638                        controller=StatsController, action='
get_meter_stats',
639                        conditions=dict(method=['GET']))
640
641         uri = path + '/meter/{dpid}/{meter_id}'
642         mapper.connect('stats', uri,
643                        controller=StatsController, action='
get_meter_stats',
644                        conditions=dict(method=['GET']))
645
646         uri = path + '/groupfeatures/{dpid}'
647         mapper.connect('stats', uri,
648                        controller=StatsController, action='
get_group_features',
649                        conditions=dict(method=['GET']))
650
651         uri = path + '/groupdesc/{dpid}'
652         mapper.connect('stats', uri,
653                        controller=StatsController, action='
get_group_desc',
654                        conditions=dict(method=['GET']))
655
656         uri = path + '/groupdesc/{dpid}/{group_id}'
657         mapper.connect('stats', uri,
658                        controller=StatsController, action='
get_group_desc',
659                        conditions=dict(method=['GET']))
660
661         uri = path + '/group/{dpid}'

```

```

662     mapper.connect('stats', uri,
663                   controller=StatsController, action='
get_group_stats',
664                   conditions=dict(method=['GET']))
665
666     uri = path + '/group/{dpid}/{group_id}'
667     mapper.connect('stats', uri,
668                   controller=StatsController, action='
get_group_stats',
669                   conditions=dict(method=['GET']))
670
671     uri = path + '/portdesc/{dpid}'
672     mapper.connect('stats', uri,
673                   controller=StatsController, action='get_port_desc
',
674                   conditions=dict(method=['GET']))
675
676     uri = path + '/portdesc/{dpid}/{port_no}'
677     mapper.connect('stats', uri,
678                   controller=StatsController, action='get_port_desc
',
679                   conditions=dict(method=['GET']))
680
681     uri = path + '/role/{dpid}'
682     mapper.connect('stats', uri,
683                   controller=StatsController, action='get_role',
684                   conditions=dict(method=['GET']))
685
686     uri = path + '/flowentry/{cmd}'
687     mapper.connect('stats', uri,
688                   controller=StatsController, action='
mod_flow_entry',
689                   conditions=dict(method=['POST']))
690
691     uri = path + '/flowentry/clear/{dpid}'
692     mapper.connect('stats', uri,
693                   controller=StatsController, action='
delete_flow_entry',
694                   conditions=dict(method=['DELETE']))
695
696     uri = path + '/meterentry/{cmd}'
697     mapper.connect('stats', uri,
698                   controller=StatsController, action='
mod_meter_entry',
699                   conditions=dict(method=['POST']))
700
701     uri = path + '/groupentry/{cmd}'
702     mapper.connect('stats', uri,
703                   controller=StatsController, action='
mod_group_entry',
704                   conditions=dict(method=['POST']))
705
706     uri = path + '/portdesc/{cmd}'
707     mapper.connect('stats', uri,

```



```

708         controller=StatsController , action='
mod_port_behavior' ,
709         conditions=dict(method=['POST' ]))
710
711     uri = path + '/experimenter/{dpid}'
712     mapper.connect('stats' , uri ,
713         controller=StatsController , action='
send_experimenter' ,
714         conditions=dict(method=['POST' ]))
715
716     uri = path + '/role'
717     mapper.connect('stats' , uri ,
718         controller=StatsController , action='set_role' ,
719         conditions=dict(method=['POST' ]))
720
721 @set_ev_cls ([ ofp_event.EventOFPPStatsReply ,
722               ofp_event.EventOFPPDescStatsReply ,
723               ofp_event.EventOFPPFlowStatsReply ,
724               ofp_event.EventOFPPAggregateStatsReply ,
725               ofp_event.EventOFPPTableStatsReply ,
726               ofp_event.EventOFPPTableFeaturesStatsReply ,
727               ofp_event.EventOFPPPortStatsReply ,
728               ofp_event.EventOFPPQueueStatsReply ,
729               ofp_event.EventOFPPQueueDescStatsReply ,
730               ofp_event.EventOFPPMeterStatsReply ,
731               ofp_event.EventOFPPMeterFeaturesStatsReply ,
732               ofp_event.EventOFPPMeterConfigStatsReply ,
733               ofp_event.EventOFPPGroupStatsReply ,
734               ofp_event.EventOFPPGroupFeaturesStatsReply ,
735               ofp_event.EventOFPPGroupDescStatsReply ,
736               ofp_event.EventOFPPPortDescStatsReply
737             ], MAIN_DISPATCHER)
738 def stats_reply_handler(self , ev):
739     msg = ev.msg
740     dp = msg.datapath
741
742     if dp.id not in self.waiters:
743         return
744     if msg.xid not in self.waiters[dp.id]:
745         return
746     lock , msgs = self.waiters[dp.id][msg.xid]
747     msgs.append(msg)
748
749     flags = 0
750     if dp.ofproto.OFP_VERSION == ofproto_v1_0.OFP_VERSION:
751         flags = dp.ofproto.OFPSF_REPLY_MORE
752     elif dp.ofproto.OFP_VERSION == ofproto_v1_2.OFP_VERSION:
753         flags = dp.ofproto.OFPSF_REPLY_MORE
754     elif dp.ofproto.OFP_VERSION >= ofproto_v1_3.OFP_VERSION:
755         flags = dp.ofproto.OFPMPF_REPLY_MORE
756
757     if msg.flags & flags:
758         return
759     del self.waiters[dp.id][msg.xid]

```

```

760     lock.set()
761
762     @set_ev_cls([ ofp_event.EventOFPSwitchFeatures ,
763                  ofp_event.EventOFPPQueueGetConfigReply ,
764                  ofp_event.EventOFPPRoleReply ,
765                  ], MAIN_DISPATCHER)
766     def features_reply_handler(self, ev):
767         msg = ev.msg
768         dp = msg.datapath
769
770         if dp.id not in self.waiters:
771             return
772         if msg.xid not in self.waiters[dp.id]:
773             return
774         lock, msgs = self.waiters[dp.id][msg.xid]
775         msgs.append(msg)
776
777         del self.waiters[dp.id][msg.xid]
778         lock.set()

```

A.6 rest_conf_switch.py

```

1  # Copyright (C) 2012 Nippon Telegraph and Telephone Corporation.
2  # Copyright (C) 2012 Isaku Yamahata <yamahata at private email ne jp>
3  #
4  # Licensed under the Apache License, Version 2.0 (the "License");
5  # you may not use this file except in compliance with the License.
6  # You may obtain a copy of the License at
7  #
8  #     http://www.apache.org/licenses/LICENSE-2.0
9  #
10 # Unless required by applicable law or agreed to in writing, software
11 # distributed under the License is distributed on an "AS IS" BASIS,
12 # WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or
13 # implied.
14 # See the License for the specific language governing permissions and
15 # limitations under the License.
16
17 """
18 This module provides a set of REST API for switch configuration.
19 - Per-switch Key-Value store
20
21 Used by OpenStack Ryu agent.
22 """
23
24 import json
25
26 from six.moves import http_client
27
28 from ryu.app.wsgi import ControllerBase
29 from ryu.app.wsgi import Response

```

```

30 from ryu.base import app_manager
31 from ryu.controller import conf_switch
32 from ryu.lib import dpid as dpid_lib
33
34
35 # REST API for switch configuration
36 #
37 # get all the switches
38 # GET /v1.0/conf/switches
39 #
40 # get all the configuration keys of a switch
41 # GET /v1.0/conf/switches/<dpid>
42 #
43 # delete all the configuration of a switch
44 # DELETE /v1.0/conf/switches/<dpid>
45 #
46 # set the <key> configuration of a switch
47 # PUT /v1.0/conf/switches/<dpid>/<key>
48 #
49 # get the <key> configuration of a switch
50 # GET /v1.0/conf/switches/<dpid>/<key>
51 #
52 # delete the <key> configuration of a switch
53 # DELETE /v1.0/conf/switches/<dpid>/<key>
54 #
55 # where
56 # <dpid>: datapath id in 16 hex
57
58
59 class ConfSwitchController(ControllerBase):
60     def __init__(self, req, link, data, **config):
61         super(ConfSwitchController, self).__init__(req, link, data, **
62 config)
63         self.conf_switch = data
64
65     def list_switches(self, _req, **_kwargs):
66         dpids = self.conf_switch.dpids()
67         body = json.dumps([ dpid_lib.dpid_to_str(dpid) for dpid in dpids
68 ])
69         return Response(content_type='application/json', body=body)
70
71     @staticmethod
72     def _do_switch(dpid, func, ret_func):
73         dpid = dpid_lib.str_to_dpid(dpid)
74         try:
75             ret = func(dpid)
76         except KeyError:
77             return Response(status=http_client.NOT_FOUND,
78                             body='no dpid is found %s' %
79 dpid_lib.dpid_to_str(dpid))
80
81         return ret_func(ret)
82
83     def delete_switch(self, _req, dpid, **_kwargs):

```

```

82     def _delete_switch(dpid):
83         self.conf_switch.del_dpid(dpid)
84         return None
85
86     def _ret(_ret):
87         return Response(status=http_client.ACCEPTED)
88
89     return self._do_switch(dpid, _delete_switch, _ret)
90
91 def list_keys(self, _req, dpid, **kwargs):
92     def _list_keys(dpid):
93         return self.conf_switch.keys(dpid)
94
95     def _ret(keys):
96         body = json.dumps(keys)
97         return Response(content_type='application/json', body=body)
98
99     return self._do_switch(dpid, _list_keys, _ret)
100
101 @staticmethod
102 def _do_key(dpid, key, func, ret_func):
103     dpid = dpid_lib.str_to_dpid(dpid)
104     try:
105         ret = func(dpid, key)
106     except KeyError:
107         return Response(status=http_client.NOT_FOUND,
108                         body='no dpid/key is found %s %s' %
109                             (dpid_lib.dpid_to_str(dpid), key))
110     return ret_func(ret)
111
112 def set_key(self, req, dpid, key, **kwargs):
113     def _set_val(dpid, key):
114         try:
115             val = req.json if req.body else {}
116         except ValueError:
117             return Response(status=http_client.BAD_REQUEST,
118                             body='invalid syntax %s' % req.body)
119         self.conf_switch.set_key(dpid, key, val)
120         return None
121
122     def _ret(_ret):
123         return Response(status=http_client.CREATED)
124
125     return self._do_key(dpid, key, _set_val, _ret)
126
127 def get_key(self, _req, dpid, key, **kwargs):
128     def _get_key(dpid, key):
129         return self.conf_switch.get_key(dpid, key)
130
131     def _ret(val):
132         return Response(content_type='application/json',
133                         body=json.dumps(val))
134
135     return self._do_key(dpid, key, _get_key, _ret)

```

```

136
137     def delete_key(self, _req, dpid, key, **kwargs):
138         def _delete_key(dpid, key):
139             self.conf_switch.del_key(dpid, key)
140             return None
141
142         def _ret(_ret):
143             return Response()
144
145         return self._do_key(dpid, key, _delete_key, _ret)
146
147
148 class ConfSwitchAPI(app_manager.RyuApp):
149     _CONTEXTS = {
150         'conf_switch': conf_switch.ConfSwitchSet,
151     }
152
153     def __init__(self, *args, **kwargs):
154         super(ConfSwitchAPI, self).__init__(*args, **kwargs)
155         self.conf_switch = kwargs['conf_switch']
156         wsgi = kwargs['wsgi']
157         mapper = wsgi.mapper
158
159         controller = ConfSwitchController
160         wsgi.registry[controller.__name__] = self.conf_switch
161         route_name = 'conf_switch'
162         uri = '/v1.0/conf/switches'
163         mapper.connect(route_name, uri, controller=controller,
164                       action='list_switches',
165                       conditions=dict(method=['GET']))
166
167         uri += '/{dpid}'
168         requirements = {'dpid': dpid_lib.DPID_PATTERN}
169         s = mapper.submapper(controller=controller, requirements=
requirements)
170         s.connect(route_name, uri, action='delete_switch',
171                 conditions=dict(method=['DELETE']))
172         s.connect(route_name, uri, action='list_keys',
173                 conditions=dict(method=['GET']))
174
175         uri += '/{key}'
176         s.connect(route_name, uri, action='set_key',
177                 conditions=dict(method=['PUT']))
178         s.connect(route_name, uri, action='get_key',
179                 conditions=dict(method=['GET']))
180         s.connect(route_name, uri, action='delete_key',
181                 conditions=dict(method=['DELETE']))

```

A.7 rest_qos.py

```
# Copyright (C) 2014 Kiyonari Harigae <lakshmi at cloudysunny14 org>
```

```

2 #
3 # Licensed under the Apache License, Version 2.0 (the "License");
4 # you may not use this file except in compliance with the License.
5 # You may obtain a copy of the License at
6 #
7 # http://www.apache.org/licenses/LICENSE-2.0
8 #
9 # Unless required by applicable law or agreed to in writing, software
10 # distributed under the License is distributed on an "AS IS" BASIS,
11 # WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or
12 # implied.
13 # See the License for the specific language governing permissions and
14 # limitations under the License.
15
16
17 import logging
18 import json
19 import re
20
21 from ryu.app import conf_switch_key as cs_key
22 from ryu.app.wsgi import ControllerBase
23 from ryu.app.wsgi import Response
24 from ryu.app.wsgi import route
25 from ryu.app.wsgi import WSGIApplication
26 from ryu.base import app_manager
27 from ryu.controller import conf_switch
28 from ryu.controller import ofp_event
29 from ryu.controller import dpset
30 from ryu.controller.handler import set_ev_cls
31 from ryu.controller.handler import MAIN_DISPATCHER
32 from ryu.exception import OFPUnknownVersion
33 from ryu.lib import dpid as dpid_lib
34 from ryu.lib import mac
35 from ryu.lib import ofctl_v1_0
36 from ryu.lib import ofctl_v1_2
37 from ryu.lib import ofctl_v1_3
38 from ryu.lib.ovs import bridge
39 from ryu.ofproto import ofproto_v1_0
40 from ryu.ofproto import ofproto_v1_2
41 from ryu.ofproto import ofproto_v1_3
42 from ryu.ofproto import ofproto_v1_3_parser
43 from ryu.ofproto import ether
44 from ryu.ofproto import inet
45
46
47 # =====
48 #           REST API
49 # =====
50 #
51 # Note: specify switch and vlan group, as follows.
52 # {switch-id} : 'all' or switchID
53 # {vlan-id}   : 'all' or vlanID
54 #
55 # about queue status

```

```

56 #
57 # get status of queue
58 # GET /qos/queue/status/{switch-id}
59 #
60 # about queues
61 # get a queue configurations
62 # GET /qos/queue/{switch-id}
63 #
64 # set a queue to the switches
65 # POST /qos/queue/{switch-id}
66 #
67 # request body format:
68 # {"port_name":"<name of port>",
69 #  "type": "<linux-htb or linux-other>",
70 #  "max-rate": "<int>",
71 #  "queues":[{"max_rate": "<int>", "min_rate": "<int>"},...]}
72 #
73 # Note: This operation override
74 #       previous configurations.
75 # Note: Queue configurations are available for
76 #       OpenvSwitch.
77 # Note: port_name is optional argument.
78 #       If does not pass the port_name argument,
79 #       all ports are target for configuration.
80 #
81 # delete queue
82 # DELETE /qos/queue/{switch-id}
83 #
84 # Note: This operation delete relation of qos record from
85 #       qos colum in Port table. Therefore,
86 #       QoS records and Queue records will remain.
87 #
88 # about qos rules
89 #
90 # get rules of qos
91 # * for no vlan
92 # GET /qos/rules/{switch-id}
93 #
94 # * for specific vlan group
95 # GET /qos/rules/{switch-id}/{vlan-id}
96 #
97 # set a qos rules
98 #
99 # QoS rules will do the processing pipeline,
100 # which entries are register the first table (by default table id 0)
101 # and process will apply and go to next table.
102 #
103 # * for no vlan
104 # POST /qos/{switch-id}
105 #
106 # * for specific vlan group
107 # POST /qos/{switch-id}/{vlan-id}
108 #
109 # request body format:

```

```

110 # {"priority": "<value>",
111 #   "match": {"<field1>": "<value1>", "<field2>": "<value2>",...},
112 #   "actions": {"<action1>": "<value1>", "<action2>": "<value2>",...}
113 # }
114 #
115 # Description
116 # * priority field
117 #   <value>
118 #   "0 to 65533"
119 #
120 # Note: When "priority" has not been set up,
121 #       "priority: 1" is set to "priority".
122 #
123 # * match field
124 #   <field> : <value>
125 #   "in_port" : "<int>"
126 #   "dl_src" : "<xx:xx:xx:xx:xx:xx>"
127 #   "dl_dst" : "<xx:xx:xx:xx:xx:xx>"
128 #   "dl_type" : "<ARP or IPv4 or IPv6>"
129 #   "nw_src" : "<A.B.C.D/M>"
130 #   "nw_dst" : "<A.B.C.D/M>"
131 #   "ipv6_src": "<xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx /M>"
132 #   "ipv6_dst": "<xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx /M>"
133 #   "nw_proto": "<TCP or UDP or ICMP or ICMPv6>"
134 #   "tp_src" : "<int>"
135 #   "tp_dst" : "<int>"
136 #   "ip-dscp" : "<int>"
137 #
138 # * actions field
139 #   <field> : <value>
140 #   "mark": <dscp-value>
141 #   sets the IPv4 ToS/DSCP field to tos.
142 #   "meter": <meter-id>
143 #   apply meter entry
144 #   "queue": <queue-id>
145 #   register queue specified by queue-id
146 #
147 # Note: When "actions" has not been set up,
148 #       "queue: 0" is set to "actions".
149 #
150 # delete a qos rules
151 # * for no vlan
152 # DELETE /qos/rule/{switch-id}
153 #
154 # * for specific vlan group
155 # DELETE /qos/{switch-id}/{vlan-id}
156 #
157 # request body format:
158 # {"<field>": "<value>"}
159 #
160 #   <field> : <value>
161 #   "qos_id" : "<int>" or "all"
162 #
163 # about meter entries

```



```

164 #
165 # set a meter entry
166 # POST /qos/meter/{switch-id}
167 #
168 # request body format:
169 #   {"meter_id": <int>,
170 #    "bands":[{"action": "<DROP or DSCP.REMARK>",
171 #              "flag": "<KBPS or PKTPS or BURST or STATS>"
172 #              "burst_size": <int>,
173 #              "rate": <int>,
174 #              "prec_level": <int>},...]}
175 #
176 # delete a meter entry
177 # DELETE /qos/meter/{switch-id}
178 #
179 # request body format:
180 #   {"<field>":"<value>"}
181 #
182 #     <field> : <value>
183 #     "meter_id" : "<int>"
184 #
185
186
187 SWITCHID_PATTERN = dpid_lib.DPID_PATTERN + r'|all'
188 VLANID_PATTERN = r'[0-9]{1,4}|all'
189
190 QOS_TABLE_ID = 0
191
192 REST_ALL = 'all'
193 REST_SWITCHID = 'switch_id'
194 REST_COMMAND_RESULT = 'command_result'
195 REST_PRIORITY = 'priority'
196 REST_VLANID = 'vlan_id'
197 REST_PORT_NAME = 'port_name'
198 REST_QUEUE_TYPE = 'type'
199 REST_QUEUE_MAX_RATE = 'max_rate'
200 REST_QUEUE_MIN_RATE = 'min_rate'
201 REST_QUEUES = 'queues'
202 REST_QOS = 'qos'
203 REST_QOS_ID = 'qos_id'
204 REST_COOKIE = 'cookie'
205
206 REST_MATCH = 'match'
207 REST_IN_PORT = 'in_port'
208 REST_SRC_MAC = 'dl_src'
209 REST_DST_MAC = 'dl_dst'
210 REST_DL_TYPE = 'dl_type'
211 REST_DL_TYPE_ARP = 'ARP'
212 REST_DL_TYPE_IPV4 = 'IPv4'
213 REST_DL_TYPE_IPV6 = 'IPv6'
214 REST_DL_VLAN = 'dl_vlan'
215 REST_SRC_IP = 'nw_src'
216 REST_DST_IP = 'nw_dst'
217 REST_SRC_IPV6 = 'ipv6_src'

```

```

218 REST_DST_IPV6 = 'ipv6_dst'
219 REST_NW_PROTO = 'nw_proto'
220 REST_NW_PROTO_TCP = 'TCP'
221 REST_NW_PROTO_UDP = 'UDP'
222 REST_NW_PROTO_ICMP = 'ICMP'
223 REST_NW_PROTO_ICMPV6 = 'ICMPv6'
224 REST_TP_SRC = 'tp_src'
225 REST_TP_DST = 'tp_dst'
226 REST_DSCP = 'ip_dscp'
227
228 REST_ACTION = 'actions'
229 REST_ACTION_QUEUE = 'queue'
230 REST_ACTION_MARK = 'mark'
231 REST_ACTION_METER = 'meter'
232
233 REST_METER_ID = 'meter_id'
234 REST_METER_BURST_SIZE = 'burst_size'
235 REST_METER_RATE = 'rate'
236 REST_METER_PREC_LEVEL = 'prec_level'
237 REST_METER_BANDS = 'bands'
238 REST_METER_ACTION_DROP = 'drop'
239 REST_METER_ACTION_REMARK = 'remark'
240
241 DEFAULT_FLOW_PRIORITY = 0
242 QOS_PRIORITY_MAX = ofproto_v1_3_parser.UINT16_MAX - 1
243 QOS_PRIORITY_MIN = 1
244
245 VLANID_NONE = 0
246 VLANID_MIN = 2
247 VLANID_MAX = 4094
248 COOKIE_SHIFT_VLANID = 32
249
250 BASE_URL = '/qos'
251 REQUIREMENTS = {'switchid': SWITCHID_PATTERN,
252                 'vlanid': VLANID_PATTERN}
253
254 LOG = logging.getLogger(__name__)
255
256
257 class RestQoSAPI(app_manager.RyuApp):
258
259     OFP_VERSIONS = [ofproto_v1_0.OFP_VERSION,
260                    ofproto_v1_2.OFP_VERSION,
261                    ofproto_v1_3.OFP_VERSION]
262
263     _CONTEXTS = {
264         'dpset': dpset.DPSet,
265         'conf_switch': conf_switch.ConfSwitchSet,
266         'wsgi': WSGIApplication}
267
268     def __init__(self, *args, **kwargs):
269         super(RestQoSAPI, self).__init__(*args, **kwargs)
270
271         # logger configure

```

```

272     QoSController.set_logger(self.logger)
273     self.cs = kwargs['conf_switch']
274     self.dpset = kwargs['dpset']
275     wsgi = kwargs['wsgi']
276     self.waiters = {}
277     self.data = {}
278     self.data['dpset'] = self.dpset
279     self.data['waiters'] = self.waiters
280     wsgi.registry['QoSController'] = self.data
281     wsgi.register(QoSController, self.data)
282
283     def stats_reply_handler(self, ev):
284         msg = ev.msg
285         dp = msg.datapath
286
287         if dp.id not in self.waiters:
288             return
289         if msg.xid not in self.waiters[dp.id]:
290             return
291         lock, msgs = self.waiters[dp.id][msg.xid]
292         msgs.append(msg)
293
294         flags = 0
295         if dp.ofproto.OFP_VERSION == ofproto_v1_0.OFP_VERSION or \
296             dp.ofproto.OFP_VERSION == ofproto_v1_2.OFP_VERSION:
297             flags = dp.ofproto.OFPSF_REPLY_MORE
298         elif dp.ofproto.OFP_VERSION == ofproto_v1_3.OFP_VERSION:
299             flags = dp.ofproto.OFPMPF_REPLY_MORE
300
301         if msg.flags & flags:
302             return
303         del self.waiters[dp.id][msg.xid]
304         lock.set()
305
306     @set_ev_cls(conf_switch.EventConfSwitchSet)
307     def conf_switch_set_handler(self, ev):
308         if ev.key == cs_key.OVSDB_ADDR:
309             QoSController.set_ovsdb_addr(ev.dpid, ev.value)
310         else:
311             QoSController.LOGGER.debug("unknown event: %s", ev)
312
313     @set_ev_cls(conf_switch.EventConfSwitchDel)
314     def conf_switch_del_handler(self, ev):
315         if ev.key == cs_key.OVSDB_ADDR:
316             QoSController.delete_ovsdb_addr(ev.dpid)
317         else:
318             QoSController.LOGGER.debug("unknown event: %s", ev)
319
320     @set_ev_cls(dpset.EventDP, dpset.DPSET_EV_DISPATCHER)
321     def handler_datapath(self, ev):
322         if ev.enter:
323             QoSController.regist_ofs(ev.dp, self.CONF)
324         else:
325             QoSController.unregist_ofs(ev.dp)

```

```

326
327 # for OpenFlow version1.0
328 @set_ev_cls(ofp_event.EventOFPPFlowStatsReply, MAIN_DISPATCHER)
329 def stats_reply_handler_v1_0(self, ev):
330     self.stats_reply_handler(ev)
331
332 # for OpenFlow version1.2 or later
333 @set_ev_cls(ofp_event.EventOFPPStatsReply, MAIN_DISPATCHER)
334 def stats_reply_handler_v1_2(self, ev):
335     self.stats_reply_handler(ev)
336
337 # for OpenFlow version1.2 or later
338 @set_ev_cls(ofp_event.EventOFPPQueueStatsReply, MAIN_DISPATCHER)
339 def queue_stats_reply_handler_v1_2(self, ev):
340     self.stats_reply_handler(ev)
341
342 # for OpenFlow version1.2 or later
343 @set_ev_cls(ofp_event.EventOFPPMeterStatsReply, MAIN_DISPATCHER)
344 def meter_stats_reply_handler_v1_2(self, ev):
345     self.stats_reply_handler(ev)
346
347
348 class QoSOfsList(dict):
349
350     def __init__(self):
351         super(QoSOfsList, self).__init__()
352
353     def get_ofs(self, dp_id):
354         if len(self) == 0:
355             raise ValueError('qos sw is not connected.')
356
357         dps = {}
358         if dp_id == REST_ALL:
359             dps = self
360         else:
361             try:
362                 dpid = dpid_lib.str_to_dpid(dp_id)
363             except:
364                 raise ValueError('Invalid switchID.')
365
366             if dpid in self:
367                 dps = {dpid: self[dpid]}
368             else:
369                 msg = 'qos sw is not connected. : switchID=%s' % dp_id
370                 raise ValueError(msg)
371
372         return dps
373
374
375 class QoSController(ControllerBase):
376
377     _OFS_LIST = QoSOfsList()
378     LOGGER = None
379

```

```

380 def __init__(self, req, link, data, **config):
381     super(QoSController, self).__init__(req, link, data, **config)
382     self.dpset = data['dpset']
383     self.waiters = data['waiters']
384
385 @classmethod
386 def set_logger(cls, logger):
387     cls.LOGGER = logger
388     cls.LOGGER.propagate = False
389     hdr = logging.StreamHandler()
390     fmt_str = '[QoS][%(levelname)s] %(message)s'
391     hdr.setFormatter(logging.Formatter(fmt_str))
392     cls.LOGGER.addHandler(hdr)
393
394 @staticmethod
395 def regist_ofs(dp, CONF):
396     if dp.id in QoSController._OFS_LIST:
397         return
398
399     dpid_str = dpid_lib.dpid_to_str(dp.id)
400     try:
401         f_ofs = QoS(dp, CONF)
402         f_ofs.set_default_flow()
403     except OFPUnknownVersion as message:
404         QoSController.LOGGER.info('dpid=%s: %s',
405                                   dpid_str, message)
406     return
407
408     QoSController._OFS_LIST.setdefault(dp.id, f_ofs)
409     QoSController.LOGGER.info('dpid=%s: Join qos switch.',
410                               dpid_str)
411
412 @staticmethod
413 def unregist_ofs(dp):
414     if dp.id in QoSController._OFS_LIST:
415         del QoSController._OFS_LIST[dp.id]
416         QoSController.LOGGER.info('dpid=%s: Leave qos switch.',
417                                   dpid_lib.dpid_to_str(dp.id))
418
419 @staticmethod
420 def set_ovsdb_addr(dpid, value):
421     ofs = QoSController._OFS_LIST.get(dpid, None)
422     if ofs is not None:
423         ofs.set_ovsdb_addr(dpid, value)
424
425 @staticmethod
426 def delete_ovsdb_addr(dpid):
427     ofs = QoSController._OFS_LIST.get(dpid, None)
428     ofs.set_ovsdb_addr(dpid, None)
429
430 @route('qos_switch', BASE_URL + '/queue/{switchid}',
431        methods=['GET'], requirements=REQUIREMENTS)
432 def get_queue(self, req, switchid, **kwargs):
433     return self._access_switch(req, switchid, VLANID_NONE,

```

```

434         'get_queue', None)
435
436 @route('qos_switch', BASE_URL + '/queue/{switchid}',
437       methods=['POST'], requirements=REQUIREMENTS)
438 def set_queue(self, req, switchid, **kwargs):
439     return self._access_switch(req, switchid, VLANID_NONE,
440                               'set_queue', None)
441
442 @route('qos_switch', BASE_URL + '/queue/{switchid}',
443       methods=['DELETE'], requirements=REQUIREMENTS)
444 def delete_queue(self, req, switchid, **kwargs):
445     return self._access_switch(req, switchid, VLANID_NONE,
446                               'delete_queue', None)
447
448 @route('qos_switch', BASE_URL + '/queue/status/{switchid}',
449       methods=['GET'], requirements=REQUIREMENTS)
450 def get_status(self, req, switchid, **kwargs):
451     return self._access_switch(req, switchid, VLANID_NONE,
452                               'get_status', self.waiters)
453
454 @route('qos_switch', BASE_URL + '/rules/{switchid}',
455       methods=['GET'], requirements=REQUIREMENTS)
456 def get_qos(self, req, switchid, **kwargs):
457     return self._access_switch(req, switchid, VLANID_NONE,
458                               'get_qos', self.waiters)
459
460 @route('qos_switch', BASE_URL + '/rules/{switchid}/{vlanid}',
461       methods=['GET'], requirements=REQUIREMENTS)
462 def get_vlan_qos(self, req, switchid, vlanid, **kwargs):
463     return self._access_switch(req, switchid, vlanid,
464                               'get_qos', self.waiters)
465
466 @route('qos_switch', BASE_URL + '/rules/{switchid}',
467       methods=['POST'], requirements=REQUIREMENTS)
468 def set_qos(self, req, switchid, **kwargs):
469     return self._access_switch(req, switchid, VLANID_NONE,
470                               'set_qos', self.waiters)
471
472 @route('qos_switch', BASE_URL + '/rules/{switchid}/{vlanid}',
473       methods=['POST'], requirements=REQUIREMENTS)
474 def set_vlan_qos(self, req, switchid, vlanid, **kwargs):
475     return self._access_switch(req, switchid, vlanid,
476                               'set_qos', self.waiters)
477
478 @route('qos_switch', BASE_URL + '/rules/{switchid}',
479       methods=['DELETE'], requirements=REQUIREMENTS)
480 def delete_qos(self, req, switchid, **kwargs):
481     return self._access_switch(req, switchid, VLANID_NONE,
482                               'delete_qos', self.waiters)
483
484 @route('qos_switch', BASE_URL + '/rules/{switchid}/{vlanid}',
485       methods=['DELETE'], requirements=REQUIREMENTS)
486 def delete_vlan_qos(self, req, switchid, vlanid, **kwargs):
487     return self._access_switch(req, switchid, vlanid,

```

```

488         'delete_qos', self.waiters)
489
490     @route('qos_switch', BASE_URL + '/meter/{switchid}',
491           methods=['GET'], requirements=REQUIREMENTS)
492     def get_meter(self, req, switchid, **kwargs):
493         return self._access_switch(req, switchid, VLANID_NONE,
494                                   'get_meter', self.waiters)
495
496     @route('qos_switch', BASE_URL + '/meter/{switchid}',
497           methods=['POST'], requirements=REQUIREMENTS)
498     def set_meter(self, req, switchid, **kwargs):
499         return self._access_switch(req, switchid, VLANID_NONE,
500                                   'set_meter', self.waiters)
501
502     @route('qos_switch', BASE_URL + '/meter/{switchid}',
503           methods=['DELETE'], requirements=REQUIREMENTS)
504     def delete_meter(self, req, switchid, **kwargs):
505         return self._access_switch(req, switchid, VLANID_NONE,
506                                   'delete_meter', self.waiters)
507
508     def _access_switch(self, req, switchid, vlan_id, func, waiters):
509         try:
510             rest = req.json if req.body else {}
511         except ValueError:
512             QoSController.LOGGER.debug('invalid syntax %s', req.body)
513             return Response(status=400)
514
515         try:
516             dps = self._OFS_LIST.get_ofs(switchid)
517             vid = QoSController._conv_toint_vlanid(vlan_id)
518         except ValueError as message:
519             return Response(status=400, body=str(message))
520
521         msgs = []
522         for f_ofs in dps.values():
523             function = getattr(f_ofs, func)
524             try:
525                 if waiters is not None:
526                     msg = function(rest, vid, waiters)
527                 else:
528                     msg = function(rest, vid)
529             except ValueError as message:
530                 return Response(status=400, body=str(message))
531             msgs.append(msg)
532
533         body = json.dumps(msgs)
534         return Response(content_type='application/json', body=body)
535
536     @staticmethod
537     def _conv_toint_vlanid(vlan_id):
538         if vlan_id != REST_ALL:
539             vlan_id = int(vlan_id)
540             if (vlan_id != VLANID_NONE and
541                 (vlan_id < VLANID_MIN or VLANID_MAX < vlan_id)):

```

```

542         msg = 'Invalid {vlan_id} value. Set [%d-%d]' % (
VLANID.MIN,
543
VLANID.MAX)
544         raise ValueError(msg)
545         return vlan_id
546
547
548 class QoS(object):
549
550     _OFCTL = {ofproto_v1_0.OFP_VERSION: ofctl_v1_0 ,
551              ofproto_v1_2.OFP_VERSION: ofctl_v1_2 ,
552              ofproto_v1_3.OFP_VERSION: ofctl_v1_3}
553
554     def __init__(self, dp, CONF):
555         super(QoS, self).__init__()
556         self.vlan_list = {}
557         self.vlan_list[VLANID.NONE] = 0 # for VLAN=None
558         self.dp = dp
559         self.version = dp.ofproto.OFP_VERSION
560         self.queue_list = {}
561         self.CONF = CONF
562         self.ovsdb_addr = None
563         self.ovs_bridge = None
564
565         if self.version not in self._OFCTL:
566             raise OFPUnknownVersion(version=self.version)
567
568         self.ofctl = self._OFCTL[self.version]
569
570     def set_default_flow(self):
571         if self.version == ofproto_v1_0.OFP_VERSION:
572             return
573
574         cookie = 0
575         priority = DEFAULT_FLOW_PRIORITY
576         actions = [{'type': 'GOTO_TABLE',
577                   'table_id': QOS_TABLE_ID + 1}]
578         flow = self._to_of_flow(cookie=cookie,
579                                priority=priority,
580                                match={},
581                                actions=actions)
582
583         cmd = self.dp.ofproto.OFPFC_ADD
584         self.ofctl.mod_flow_entry(self.dp, flow, cmd)
585
586     def set_ovsdb_addr(self, dpid, ovsdb_addr):
587         # easy check if the address format valid
588         _proto, _host, _port = ovsdb_addr.split(':')
589
590         old_address = self.ovsdb_addr
591         if old_address == ovsdb_addr:
592             return
593         if ovsdb_addr is None:

```



```

594         if self.ovs_bridge:
595             self.ovs_bridge.del_controller()
596             self.ovs_bridge = None
597         return
598     self.ovsdb_addr = ovsdb_addr
599     if self.ovs_bridge is None:
600         ovs_bridge = bridge.OVSBridge(self.CONF, dpid, ovsdb_addr)
601         self.ovs_bridge = ovs_bridge
602         try:
603             ovs_bridge.init()
604         except:
605             raise ValueError('ovsdb addr is not available.')
606
607     def _update_vlan_list(self, vlan_list):
608         for vlan_id in self.vlan_list.keys():
609             if vlan_id is not VLANID_NONE and vlan_id not in vlan_list:
610                 del self.vlan_list[vlan_id]
611
612     def _get_cookie(self, vlan_id):
613         if vlan_id == REST_ALL:
614             vlan_ids = self.vlan_list.keys()
615         else:
616             vlan_ids = [vlan_id]
617
618         cookie_list = []
619         for vlan_id in vlan_ids:
620             self.vlan_list.setdefault(vlan_id, 0)
621             self.vlan_list[vlan_id] += 1
622             self.vlan_list[vlan_id] &= ofproto_v1_3_parser.UINT32_MAX
623             cookie = (vlan_id << COOKIE_SHIFT_VLANID) + \
624                 self.vlan_list[vlan_id]
625             cookie_list.append([cookie, vlan_id])
626
627         return cookie_list
628
629     @staticmethod
630     def _cookie_to_qosid(cookie):
631         return cookie & ofproto_v1_3_parser.UINT32_MAX
632
633     # REST command template
634     def rest_command(func):
635         def _rest_command(*args, **kwargs):
636             key, value = func(*args, **kwargs)
637             switch_id = dpid_lib.dpid_to_str(args[0].dp.id)
638             return {REST_SWITCHID: switch_id,
639                     key: value}
640         return _rest_command
641
642     @rest_command
643     def get_status(self, req, vlan_id, waiters):
644         if self.version == ofproto_v1_0.OFP_VERSION:
645             raise ValueError('get_status operation is not supported')
646
647         msgs = self.ofctl.get_queue_stats(self.dp, waiters)

```

```

648         return REST.COMMAND.RESULT, msg
649
650     @rest_command
651     def get_queue(self, rest, vlan_id):
652         if len(self.queue_list):
653             msg = {'result': 'success',
654                  'details': self.queue_list}
655         else:
656             msg = {'result': 'failure',
657                  'details': 'Queue is not exists.'}
658
659         return REST.COMMAND.RESULT, msg
660
661     @rest_command
662     def set_queue(self, rest, vlan_id):
663         if self.ovs_bridge is None:
664             msg = {'result': 'failure',
665                  'details': 'ovs_bridge is not exists'}
666         return REST.COMMAND.RESULT, msg
667
668         self.queue_list.clear()
669         queue_type = rest.get(REST.QUEUE.TYPE, 'linux-htb')
670         parent_max_rate = rest.get(REST.QUEUE.MAX_RATE, None)
671         queues = rest.get(REST.QUEUES, [])
672         queue_id = 0
673         queue_config = []
674         for queue in queues:
675             max_rate = queue.get(REST.QUEUE.MAX_RATE, None)
676             min_rate = queue.get(REST.QUEUE.MIN_RATE, None)
677             if max_rate is None and min_rate is None:
678                 raise ValueError('Required to specify max_rate or
679 min_rate')
680             config = {}
681             if max_rate is not None:
682                 config['max-rate'] = max_rate
683             if min_rate is not None:
684                 config['min-rate'] = min_rate
685             if len(config):
686                 queue_config.append(config)
687             self.queue_list[queue_id] = {'config': config}
688             queue_id += 1
689
690         port_name = rest.get(REST.PORT.NAME, None)
691         vif_ports = self.ovs_bridge.get_port_name_list()
692
693         if port_name is not None:
694             if port_name not in vif_ports:
695                 raise ValueError('%s port is not exists' % port_name)
696             vif_ports = [port_name]
697
698         for port_name in vif_ports:
699             try:
700                 self.ovs_bridge.set_qos(port_name, type=queue_type,

```

```

701                                     queues=queue_config)
702     except Exception as msg:
703         raise ValueError(msg)
704
705     msg = {'result': 'success',
706           'details': self.queue_list}
707
708     return REST.COMMAND.RESULT, msg
709
710     def _delete_queue(self):
711         if self.ovs_bridge is None:
712             return False
713
714         vif_ports = self.ovs_bridge.get_external_ports()
715         for port in vif_ports:
716             self.ovs_bridge.del_qos(port.port_name)
717         return True
718
719     @rest_command
720     def delete_queue(self, rest, vlan_id):
721         self.queue_list.clear()
722         if self._delete_queue():
723             msg = 'success'
724         else:
725             msg = 'failure'
726
727         return REST.COMMAND.RESULT, msg
728
729     @rest_command
730     def set_qos(self, rest, vlan_id, waiters):
731         msgs = []
732         cookie_list = self._get_cookie(vlan_id)
733         for cookie, vid in cookie_list:
734             msg = self._set_qos(cookie, rest, waiters, vid)
735             msgs.append(msg)
736         return REST.COMMAND.RESULT, msgs
737
738     def _set_qos(self, cookie, rest, waiters, vlan_id):
739         match_value = rest[REST.MATCH]
740         if vlan_id:
741             match_value[REST_DL_VLAN] = vlan_id
742
743         priority = int(rest.get(REST.PRIORITY, QOS.PRIORITY_MIN))
744         if (QOS.PRIORITY_MAX < priority):
745             raise ValueError('Invalid priority value. Set [%d-%d]'
746                               % (QOS.PRIORITY_MIN, QOS.PRIORITY_MAX))
747
748         match = Match.to_openflow(match_value)
749
750         actions = []
751         action = rest.get(REST.ACTION, None)
752         if action is not None:
753             if REST.ACTION_MARK in action:
754                 actions.append({'type': 'SET_FIELD',

```

```

755         'field': REST_DSCP,
756         'value': int(action[REST_ACTION_MARK])})
757     if REST_ACTION_METER in action:
758         actions.append({'type': 'METER',
759                        'meter_id': action[REST_ACTION_METER]})
760     if REST_ACTION_QUEUE in action:
761         actions.append({'type': 'SET_QUEUE',
762                        'queue_id': action[REST_ACTION_QUEUE]})
763     else:
764         actions.append({'type': 'SET_QUEUE',
765                        'queue_id': 0})
766
767     actions.append({'type': 'GOTO_TABLE',
768                   'table_id': QOS_TABLE_ID + 1})
769     flow = self._to_of_flow(cookie=cookie, priority=priority,
770                             match=match, actions=actions)
771
772     cmd = self.dp.ofproto.OFPFC_ADD
773     try:
774         self.ofctl.mod_flow_entry(self.dp, flow, cmd)
775     except:
776         raise ValueError('Invalid rule parameter.')
777
778     qos_id = QoS._cookie_to_qosid(cookie)
779     msg = {'result': 'success',
780           'details': 'QoS added. : qos_id=%d' % qos_id}
781
782     if vlan_id != VLANID_NONE:
783         msg.setdefault(REST_VLANID, vlan_id)
784     return msg
785
786 @rest_command
787 def get_qos(self, rest, vlan_id, waiters):
788     rules = {}
789     msgs = self.ofctl.get_flow_stats(self.dp, waiters)
790     if str(self.dp.id) in msgs:
791         flow_stats = msgs[str(self.dp.id)]
792         for flow_stat in flow_stats:
793             if flow_stat['table_id'] != QOS_TABLE_ID:
794                 continue
795             priority = flow_stat[REST_PRIORITY]
796             if priority != DEFAULT_FLOW_PRIORITY:
797                 vid = flow_stat[REST_MATCH].get(REST_DL_VLAN,
VLANID_NONE)
798                 if vlan_id == REST_ALL or vlan_id == vid:
799                     rule = self._to_rest_rule(flow_stat)
800                     rules.setdefault(vid, [])
801                     rules[vid].append(rule)
802
803     get_data = []
804     for vid, rule in rules.items():
805         if vid == VLANID_NONE:
806             vid_data = {REST_QOS: rule}
807         else:

```

```

808         vid_data = {REST_VLANID: vid, REST_QOS: rule}
809         get_data.append(vid_data)
810
811     return REST.COMMAND.RESULT, get_data
812
813 @rest_command
814 def delete_qos(self, rest, vlan_id, waiters):
815     try:
816         if rest[REST_QOS_ID] == REST_ALL:
817             qos_id = REST_ALL
818         else:
819             qos_id = int(rest[REST_QOS_ID])
820     except:
821         raise ValueError('Invalid qos id.')
822
823     vlan_list = []
824     delete_list = []
825
826     msgs = self.ofctl.get_flow_stats(self.dp, waiters)
827     if str(self.dp.id) in msgs:
828         flow_stats = msgs[str(self.dp.id)]
829         for flow_stat in flow_stats:
830             cookie = flow_stat[REST_COOKIE]
831             ruleid = QoS._cookie_to_qosid(cookie)
832             priority = flow_stat[REST_PRIORITY]
833             dl_vlan = flow_stat[REST_MATCH].get(REST_DL_VLAN,
VLANID_NONE)
834
835             if priority != DEFAULT_FLOW_PRIORITY:
836                 if ((qos_id == REST_ALL or qos_id == ruleid) and
837                     (vlan_id == dl_vlan or vlan_id == REST_ALL))
838                 :
839                     match = Match.to_mod_openflow(flow_stat[
REST_MATCH])
840                     delete_list.append([cookie, priority, match])
841                 else:
842                     if dl_vlan not in vlan_list:
843                         vlan_list.append(dl_vlan)
844
845     self._update_vlan_list(vlan_list)
846
847     if len(delete_list) == 0:
848         msg_details = 'QoS rule is not exist.'
849         if qos_id != REST_ALL:
850             msg_details += ' : QoS ID=%d' % qos_id
851         msg = {'result': 'failure',
852              'details': msg_details}
853     else:
854         cmd = self.dp.ofproto.OFPFC_DELETE_STRICT
855         actions = []
856         delete_ids = {}
857         for cookie, priority, match in delete_list:
858             flow = self._to_of_flow(cookie=cookie, priority=priority

```

```

858             match=match, actions=actions)
859         self.ofctl.mod_flow_entry(self.dp, flow, cmd)
860
861         vid = match.get(REST_DL_VLAN, VLANID_NONE)
862         rule_id = QoS._cookie_to_qosid(cookie)
863         delete_ids.setdefault(vid, '')
864         delete_ids[vid] += ((' %d' if delete_ids[vid] == ''
865                             else ',%d') % rule_id)
866
867         msg = []
868         for vid, rule_ids in delete_ids.items():
869             del_msg = {'result': 'success',
870                       'details': 'deleted. : QoS ID=%s' % rule_ids}
871     }
872
873     if vid != VLANID_NONE:
874         del_msg.setdefault(REST_VLANID, vid)
875         msg.append(del_msg)
876
877     return REST_COMMAND_RESULT, msg
878
879 @rest_command
880 def set_meter(self, rest, vlan_id, waiters):
881     if self.version == ofproto_v1_0.OFP_VERSION:
882         raise ValueError('set_meter operation is not supported')
883
884     msgs = []
885     msg = self._set_meter(rest, waiters)
886     msgs.append(msg)
887     return REST_COMMAND_RESULT, msgs
888
889 def _set_meter(self, rest, waiters):
890     cmd = self.dp.ofproto.OFPMC_ADD
891     try:
892         self.ofctl.mod_meter_entry(self.dp, rest, cmd)
893     except:
894         raise ValueError('Invalid meter parameter.')
895
896     msg = {'result': 'success',
897           'details': 'Meter added. : Meter ID=%s' %
898                 rest[REST_METER_ID]}
899     return msg
900
901 @rest_command
902 def get_meter(self, rest, vlan_id, waiters):
903     if (self.version == ofproto_v1_0.OFP_VERSION or
904         self.version == ofproto_v1_2.OFP_VERSION):
905         raise ValueError('get_meter operation is not supported')
906
907     msgs = self.ofctl.get_meter_stats(self.dp, waiters)
908     return REST_COMMAND_RESULT, msgs
909
910 @rest_command
911 def delete_meter(self, rest, vlan_id, waiters):
912     if (self.version == ofproto_v1_0.OFP_VERSION or

```

```

911         self.version == ofproto_v1_2.OFP_VERSION):
912             raise ValueError('delete_meter operation is not supported')
913
914     cmd = self.dp.ofproto.OFPMC_DELETE
915     try:
916         self.ofctl.mod_meter_entry(self.dp, rest, cmd)
917     except:
918         raise ValueError('Invalid meter parameter.')
919
920     msg = {'result': 'success',
921           'details': 'Meter deleted. : Meter ID=%s' %
922                   rest[REST_METER_ID]}
923     return REST_COMMAND_RESULT, msg
924
925     def _to_of_flow(self, cookie, priority, match, actions):
926         flow = {'cookie': cookie,
927               'priority': priority,
928               'flags': 0,
929               'idle_timeout': 0,
930               'hard_timeout': 0,
931               'match': match,
932               'actions': actions}
933     return flow
934
935     def _to_rest_rule(self, flow):
936         ruleid = QoS._cookie_to_qosid(flow[REST_COOKIE])
937         rule = {REST_QOS_ID: ruleid}
938         rule.update({REST_PRIORITY: flow[REST_PRIORITY]})
939         rule.update(Match.to_rest(flow))
940         rule.update(Action.to_rest(flow))
941     return rule
942
943
944     class Match(object):
945
946         _CONVERT = {REST_DL_TYPE:
947                   {REST_DL_TYPE_ARP: ether.ETH_TYPE_ARP,
948                     REST_DL_TYPE_IPV4: ether.ETH_TYPE_IP,
949                     REST_DL_TYPE_IPV6: ether.ETH_TYPE_IPV6},
950                   REST_NW_PROTO:
951                   {REST_NW_PROTO_TCP: inet.IPPROTO_TCP,
952                     REST_NW_PROTO_UDP: inet.IPPROTO_UDP,
953                     REST_NW_PROTO_ICMP: inet.IPPROTO_ICMP,
954                     REST_NW_PROTO_ICMPV6: inet.IPPROTO_ICMPV6}}
955
956         @staticmethod
957         def to_openflow(rest):
958
959             def __inv_combi(msg):
960                 raise ValueError('Invalid combination: [%s]' % msg)
961
962             def __inv_2and1(*args):
963                 __inv_combi('%s=%s and %s' % (args[0], args[1], args[2]))
964

```

```

965 def __inv_2and2(*args):
966     __inv_combi('%s=%s and %s=%s' % (
967         args[0], args[1], args[2], args[3]))
968
969 def __inv_1and1(*args):
970     __inv_combi('%s and %s' % (args[0], args[1]))
971
972 def __inv_1and2(*args):
973     __inv_combi('%s and %s=%s' % (args[0], args[1], args[2]))
974
975 match = {}
976
977 # error check
978 dl_type = rest.get(REST_DL_TYPE)
979 nw_proto = rest.get(REST_NW_PROTO)
980 if dl_type is not None:
981     if dl_type == REST_DL_TYPE_ARP:
982         if REST_SRC_IPV6 in rest:
983             __inv_2and1(
984                 REST_DL_TYPE, REST_DL_TYPE_ARP, REST_SRC_IPV6)
985         if REST_DST_IPV6 in rest:
986             __inv_2and1(
987                 REST_DL_TYPE, REST_DL_TYPE_ARP, REST_DST_IPV6)
988         if REST_DSCP in rest:
989             __inv_2and1(
990                 REST_DL_TYPE, REST_DL_TYPE_ARP, REST_DSCP)
991         if nw_proto:
992             __inv_2and1(
993                 REST_DL_TYPE, REST_DL_TYPE_ARP, REST_NW_PROTO)
994     elif dl_type == REST_DL_TYPE_IPV4:
995         if REST_SRC_IPV6 in rest:
996             __inv_2and1(
997                 REST_DL_TYPE, REST_DL_TYPE_IPV4, REST_SRC_IPV6)
998         if REST_DST_IPV6 in rest:
999             __inv_2and1(
1000                 REST_DL_TYPE, REST_DL_TYPE_IPV4, REST_DST_IPV6)
1001         if nw_proto == REST_NW_PROTO_ICMPV6:
1002             __inv_2and2(
1003                 REST_DL_TYPE, REST_DL_TYPE_IPV4,
1004                 REST_NW_PROTO, REST_NW_PROTO_ICMPV6)
1005     elif dl_type == REST_DL_TYPE_IPV6:
1006         if REST_SRC_IP in rest:
1007             __inv_2and1(
1008                 REST_DL_TYPE, REST_DL_TYPE_IPV6, REST_SRC_IP)
1009         if REST_DST_IP in rest:
1010             __inv_2and1(
1011                 REST_DL_TYPE, REST_DL_TYPE_IPV6, REST_DST_IP)
1012         if nw_proto == REST_NW_PROTO_ICMP:
1013             __inv_2and2(
1014                 REST_DL_TYPE, REST_DL_TYPE_IPV6,
1015                 REST_NW_PROTO, REST_NW_PROTO_ICMP)
1016     else:
1017         raise ValueError('Unknown dl_type : %s' % dl_type)
1018 else:

```



```

1019     if REST_SRC_IP in rest:
1020         if REST_SRC_IPV6 in rest:
1021             __inv_1and1(REST_SRC_IP, REST_SRC_IPV6)
1022         if REST_DST_IPV6 in rest:
1023             __inv_1and1(REST_SRC_IP, REST_DST_IPV6)
1024         if nw_proto == REST_NW_PROTO_ICMPV6:
1025             __inv_1and2(
1026                 REST_SRC_IP, REST_NW_PROTO, REST_NW_PROTO_ICMPV6
1027     )
1028     rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
1029     elif REST_DST_IP in rest:
1030         if REST_SRC_IPV6 in rest:
1031             __inv_1and1(REST_DST_IP, REST_SRC_IPV6)
1032         if REST_DST_IPV6 in rest:
1033             __inv_1and1(REST_DST_IP, REST_DST_IPV6)
1034         if nw_proto == REST_NW_PROTO_ICMPV6:
1035             __inv_1and2(
1036                 REST_DST_IP, REST_NW_PROTO, REST_NW_PROTO_ICMPV6
1037     )
1038     rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
1039     elif REST_SRC_IPV6 in rest:
1040         if nw_proto == REST_NW_PROTO_ICMP:
1041             __inv_1and2(
1042                 REST_SRC_IPV6, REST_NW_PROTO, REST_NW_PROTO_ICMP
1043     )
1044     rest[REST_DL_TYPE] = REST_DL_TYPE_IPV6
1045     elif REST_DST_IPV6 in rest:
1046         if nw_proto == REST_NW_PROTO_ICMP:
1047             __inv_1and2(
1048                 REST_DST_IPV6, REST_NW_PROTO, REST_NW_PROTO_ICMP
1049     )
1050     rest[REST_DL_TYPE] = REST_DL_TYPE_IPV6
1051     elif REST_DSCP in rest:
1052         # Apply dl_type ipv4, if doesn't specify dl_type
1053         rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
1054     else:
1055         if nw_proto == REST_NW_PROTO_ICMP:
1056             rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
1057         elif nw_proto == REST_NW_PROTO_ICMPV6:
1058             rest[REST_DL_TYPE] = REST_DL_TYPE_IPV6
1059         elif nw_proto == REST_NW_PROTO_TCP or \
1060              nw_proto == REST_NW_PROTO_UDP:
1061             raise ValueError('no dl_type was specified')
1062         else:
1063             raise ValueError('Unknown nw_proto: %s' % nw_proto)
1064     for key, value in rest.items():
1065         if key in Match._CONVERT:
1066             if value in Match._CONVERT[key]:
1067                 match.setdefault(key, Match._CONVERT[key][value])
1068             else:
1069                 raise ValueError('Invalid rule parameter. : key=%s'
1070 % key)
1071     else:

```

```

1068         match.setdefault(key, value)
1069
1070     return match
1071
1072 @staticmethod
1073 def to_rest(openflow):
1074     of_match = openflow[REST_MATCH]
1075
1076     mac_dontcare = mac.haddr_to_str(mac.DONTCARE)
1077     ip_dontcare = '0.0.0.0'
1078     ipv6_dontcare = '::'
1079
1080     match = {}
1081     for key, value in of_match.items():
1082         if key == REST_SRC_MAC or key == REST_DST_MAC:
1083             if value == mac_dontcare:
1084                 continue
1085             elif key == REST_SRC_IP or key == REST_DST_IP:
1086                 if value == ip_dontcare:
1087                     continue
1088             elif key == REST_SRC_IPV6 or key == REST_DST_IPV6:
1089                 if value == ipv6_dontcare:
1090                     continue
1091             elif value == 0:
1092                 continue
1093
1094             if key in Match._CONVERT:
1095                 conv = Match._CONVERT[key]
1096                 conv = dict((value, key) for key, value in conv.items())
1097                 match.setdefault(key, conv[value])
1098             else:
1099                 match.setdefault(key, value)
1100
1101     return match
1102
1103 @staticmethod
1104 def to_mod_openflow(of_match):
1105     mac_dontcare = mac.haddr_to_str(mac.DONTCARE)
1106     ip_dontcare = '0.0.0.0'
1107     ipv6_dontcare = '::'
1108
1109     match = {}
1110     for key, value in of_match.items():
1111         if key == REST_SRC_MAC or key == REST_DST_MAC:
1112             if value == mac_dontcare:
1113                 continue
1114             elif key == REST_SRC_IP or key == REST_DST_IP:
1115                 if value == ip_dontcare:
1116                     continue
1117             elif key == REST_SRC_IPV6 or key == REST_DST_IPV6:
1118                 if value == ipv6_dontcare:
1119                     continue
1120             elif value == 0:
1121                 continue

```

```

1122         match.setdefault(key, value)
1123
1124     return match
1125
1126
1127
1128 class Action(object):
1129
1130     @staticmethod
1131     def to_rest(flow):
1132         if REST_ACTION in flow:
1133             actions = []
1134             for act in flow[REST_ACTION]:
1135                 field_value = re.search('SET_FIELD: \{ip_dscp:(\d+)\}',
act)
1136
1137                 if field_value:
1138                     actions.append({REST_ACTION_MARK: field_value.group
(1)})
1139
1140                 meter_value = re.search('METER:(\d+)\}', act)
1141                 if meter_value:
1142                     actions.append({REST_ACTION_METER: meter_value.group
(1)})
1143
1144                 queue_value = re.search('SET_QUEUE:(\d+)\}', act)
1145                 if queue_value:
1146                     actions.append({REST_ACTION_QUEUE: queue_value.group
(1)})
1147
1148                 action = {REST_ACTION: actions}
1149             else:
1150                 action = {REST_ACTION: 'Unknown action type.'}
1151
1152     return action

```

A.8 Topology_qos_TRAFFIC_GEN.py

```

1 from mininet.net import Mininet
2 from mininet.node import Controller, RemoteController, OVSController
3 from mininet.node import CPULimitedHost, Host, Node
4 from mininet.node import OVSKernelSwitch, UserSwitch
5 from mininet.node import IVSSwitch
6 from mininet.cli import CLI
7 from mininet.log import setLogLevel, info
8 from mininet.link import TCLink, Intf
9 from subprocess import call
10 import threading
11 import subprocess
12 import random
13 import os
14 import time
15 import datetime
16 import json
17 import sys

```

```

18 import ditg
19
20 from Controller_commands import *
21
22
23 def myNetwork():
24     max_rate_queue=100#Mbps
25     max_rate_queue=max_rate_queue*1000000
26     Default=str(max_rate_queue*20/100)#20%
27     Premium=str(max_rate_queue*80/100)#80%
28     Gold=str(max_rate_queue*100/100)#100%
29
30     change_values=6#change every number*5 minutes
31     Q0=False
32     #Stress Queue 1 (2,4,6,7)
33     Q1=False
34     #Stress Queue 2 (5)
35     Q2=False
36     #multiplier initialization
37     F0_max=2
38     F1_max=300
39     F2_max=300
40     F0=1
41     F1=1
42     F2=1
43
44     net=Mininet( topo=None,
45                 build=False,
46                 ipBase='10.0.0.0/8')
47
48     info( '***Adding controller\n')
49     c0=net.addController(name='c0',
50                         controller=RemoteController,
51                         ip='127.0.0.1',
52                         protocol='tcp',
53                         port=6633)
54
55     info( '***Adding switches\n')
56     s1 = net.addSwitch('s1', dpid='0000000000000001', protocols="
OpenFlow13")
57     s2 = net.addSwitch('s2', dpid='0000000000000002', protocols="
OpenFlow13")
58
59     info( '***Adding Host\n')
60     h0 = net.addHost('h0', ip='10.10/24', mac='00:00:00:00:00:0a')
61     h1 = net.addHost('h1', ip='10.11/24', mac='00:00:00:00:00:0b')
62     h2 = net.addHost('h2', ip='10.12/24', mac='00:00:00:00:00:0c')
63     h3 = net.addHost('h3', ip='10.13/24', mac='00:00:00:00:00:0d')
64     h4 = net.addHost('h4', ip='10.14/24', mac='00:00:00:00:00:0e')
65     h5 = net.addHost('h5', ip='10.15/24', mac='00:00:00:00:00:0f')
66
67     info( '***Adding Link\n')
68     net.addLink(s1, s2, 2, 2)
69

```

```

70 net.addLink(s1 , h0,3,0)
71 net.addLink(s1 , h1,4,0)
72 net.addLink(s1 , h2,5,0)
73 net.addLink(s2 , h3,3,0)
74 net.addLink(s2 , h4,4,0)
75 net.addLink(s2 , h5,5,0)
76
77 info( '***Starting Network\n')
78 net.build()
79
80 info( '***Starting Controllers\n')
81 for controller in net.controllers:
82     controller.start()
83
84 info( '***Starting Switches\n')
85 net.get('s1').start([c0])
86 net.get('s2').start([c0])
87
88
89 #Activation of manager in listening on port 6632
90 os.popen("sudo -S ovs-vsctl set-manager tcp:6632", 'w').write("
Ao70pa45")
91 time.sleep(2)
92 NET = get_switchis()
93 if NET != "NO NET" and NET!="[, ]":
94     i=1
95     while i<NET.find(","):
96         mom_NET=NET[i:]
97         datapath=NET[i:i+mom_NET.find(",")]
98         i=i+mom_NET.find(",")+2
99         port_id = switch_ports_name(datapath)
100        for k in range(0, len(port_id)):
101            if len(port_id[k])<=2:
102                pp=port_id[k]
103                print pp
104                ovsctl_set_bridge(port_id[k])
105        time.sleep(0.2)
106        i=1
107        while i<NET.find(","):
108            mom_NET=NET[i:]
109            datapath=NET[i:i+mom_NET.find(",")]
110            i=i+mom_NET.find(",")+2
111            port_id = switch_ports_name(datapath)
112            ovsdb_addr(datapath)
113            IP_Flag=True
114            for index in range(0, len(port_id)):
115                if port_id[index]=="s1-eth2" or port_id[index]=="s2-eth2
":
116                    set_queue(datapath , port_id[index] , str(
max_rate_queue) , "{\max_rate\": \"+Default+"\"} , {\max_rate\": \
"+Premium+"\"} , {\min_rate\": \"+Gold+"\"}")
117                    port = port_id[index][port_id[index].find("h")+1:]
118                    if port_id[index]=="s1-eth2":
119                        IP_Destination="10.0.0.11"

```

```

120         if port_id[index]=="s2-eth2":
121             IP_Destination="10.0.0.13"
122             set_Telecom_queue(datapath, port, IP_Flag,
IP_Destination)
123         for index in range(0,len(port_id)):
124             if port_id[index]=="s1-eth4" or port_id[index]=="s2-eth3
":
125                 port = port_id[index][port_id[index].find("h")+1:]
126                 if port_id[index]=="s1-eth4":
127                     IP_Destination="10.0.0.13"
128                 if port_id[index]=="s2-eth3":
129                     IP_Destination="10.0.0.11"
130                 set_Telecom_queue(datapath, port, IP_Flag,
IP_Destination)
131
132     # Import CSV data
133     print 'Csv Import'
134     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[0], skiprows
=[0]) # serv 0 tx
135     time_values = serv.values
136     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[1], skiprows
=[0]) # serv 0 rx
137     serv_0_tx = serv.values
138     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[2], skiprows
=[0]) # serv 0 rx
139     serv_0_rx = serv.values
140     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[3], skiprows
=[0]) # serv 1 tx
141     serv_1_tx = serv.values
142     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[4], skiprows
=[0]) # serv 1 rx
143     serv_1_rx = serv.values
144     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[5], skiprows
=[0]) # serv 2 tx
145     serv_2_tx = serv.values
146     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[6], skiprows
=[0]) # serv 2 rx
147     serv_2_rx = serv.values
148     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[15], skiprows
=[0]) # serv 3 tx
149     serv_3_tx = serv.values
150     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[16], skiprows
=[0]) # serv 3 rx
151     serv_3_rx = serv.values
152     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[11], skiprows
=[0]) # serv 4 tx
153     serv_4_tx = serv.values
154     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[12], skiprows
=[0]) # serv 4 rx
155     serv_4_rx = serv.values
156     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[7], skiprows
=[0]) # serv 5 tx
157     serv_5_tx = serv.values

```

```

158     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[8], skiprows
159     =[0]) # serv 5 rx
159     serv_5_rx = serv.values
160     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[9], skiprows
161     =[0]) # serv 6 tx
161     serv_6_tx = serv.values
162     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[10], skiprows
163     =[0]) # serv 6 rx
163     serv_6_rx = serv.values
164     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[13], skiprows
165     =[0]) # serv 7 tx
165     serv_7_tx = serv.values
166     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[14], skiprows
167     =[0]) # serv 7 rx
167     serv_7_rx = serv.values
168
169     i = 0
170     j = 0
171     # pkts
172     n = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
173     # pkts per second
174     avg = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
175     F0=F0_max
176     F1=1
177     F2=1
178     print 'Wait for time alignment'
179     wait=ditg.TIME/60
180     check_time=False
181     while check_time==False:
182         now=datetime.datetime.now()
183         time.sleep(0.1)
184         if now.minute%wait==0:
185             check_time=True
186             if len(str(now.minute))==1:
187                 starting_time=str(now.hour)+':0'+str(now.minute)
188             else:
189                 starting_time=str(now.hour)+':'+str(now.minute)
190             print starting_time
191             k=0
192             for index in time_values:
193                 if index==starting_time:
194                     i=k
195                     break
196                 k=k+1
197     print 'Starting Time: '+str(time_values[i])
198     while j < ditg.SIM_N:
199         #calculate the multipliers
200
201         if Q0:
202             if j%change_values==0:
203                 if F0==1:
204                     F0=F0_max
205                 else:
206                     F0=1

```

```

207     if Q1:
208         if j%change_values==0:
209             if F1==1:
210                 F1=F1_max
211             else:
212                 F1=1
213     if Q2:
214         if j%change_values==0:
215             if F2==1:
216                 F2=F2_max
217             else:
218                 F2=1
219
220
221
222     # Server start
223     print 'Start ITGRecv'
224     h1.cmd('ITGRecv &')
225     h3.cmd('ITGRecv &')
226     time.sleep(2)
227     # Sum of packets
228     sum_in = 0
229     sum_out = 0
230     # Serv 0 tx
231     n[0] = int(serv_0_tx[i])*F0 / ditg.SCALE + 1
232     avg[0] = n[0] / (ditg.TIME-10) + 1
233     if avg[0] > 0 and n[0] > 0:
234         com = ditg.createCmd_2(dst=ditg.dst, port="10001", tos=ditg.
SERV_0, nPkts=str(n[0]), avg=str(avg[0]))
235         print(com)
236         h1.cmd(com)
237         sum_in = sum_in + n[0]
238
239     # Serv 0 rx
240     n[0] = int(serv_0_rx[i])*F0 / ditg.SCALE + 1
241     avg[0] = n[0] / (ditg.TIME-10) + 1
242     if avg[0] > 0 and n[0] > 0:
243         com = ditg.createCmd_2(dst=ditg.src, port="10001", tos=ditg.
SERV_0, nPkts=str(n[0]), avg=str(avg[0]))
244         print(com)
245         h3.cmd(com)
246         sum_out = sum_out + n[0]
247
248     # Serv 1 tx
249     n[1] = int(serv_1_tx[i])*F0 / ditg.SCALE + 1
250     avg[1] = n[1] / (ditg.TIME-10) + 1
251     if avg[1] > 0 and n[1] > 0:
252         com = ditg.createCmd_2(dst=ditg.dst, port="10002", tos=ditg.
SERV_1, nPkts=str(n[1]), avg=str(avg[1]))
253         print(com)
254         h1.cmd(com)
255         sum_in = sum_in + n[1]
256
257     # Serv 1 rx

```



```

258     n[1] = int(serv_1_rx[i])*F0 / ditg.SCALE + 1
259     avg[1] = n[1] / (ditg.TIME-10) + 1
260     if avg[1] > 0 and n[1] > 0:
261         com = ditg.createCmd_2(dst=ditg.src , port="10002" , tos=ditg .
SERV_1, nPkts=str(n[1]), avg=str(avg[1]))
262         print(com)
263         h3.cmd(com)
264         sum_out = sum_out + n[1]
265
266     # Serv 2 tx
267     n[2] = int(serv_2_tx[i])*F1 / ditg.SCALE + 1
268     avg[2] = n[2] / (ditg.TIME-10) + 1
269     if avg[2] > 0 and n[2] > 0:
270         com = ditg.createCmd_2(dst=ditg.dst , port="10003" , tos=ditg .
SERV_2, nPkts=str(n[2]), avg=str(avg[2]))
271         print(com)
272         h1.cmd(com)
273         sum_in = sum_in + n[2]
274
275     # Serv 2 rx
276     n[2] = int(serv_2_rx[i])*F1 / ditg.SCALE + 1
277     avg[2] = n[2] / (ditg.TIME-10) + 1
278     if avg[2] > 0 and n[2] > 0:
279         com = ditg.createCmd_2(dst=ditg.src , port="10003" , tos=ditg .
SERV_2, nPkts=str(n[2]), avg=str(avg[2]))
280         print(com)
281         h3.cmd(com)
282         sum_out = sum_out + n[2]
283
284     # Serv 3 tx
285     n[3] = int(serv_3_tx[i])*F0 / ditg.SCALE + 1
286     avg[3] = n[3] / (ditg.TIME-10) + 1
287     if avg[3] > 0 and n[3] > 0:
288         com = ditg.createCmd_2(dst=ditg.dst , port="10004" , tos=ditg .
SERV_3, nPkts=str(n[3]), avg=str(avg[3]))
289         print(com)
290         h1.cmd(com)
291         sum_in = sum_in + n[3]
292
293     # Serv 3 rx
294     n[3] = int(serv_3_rx[i])*F0 / ditg.SCALE + 1
295     avg[3] = n[3] / (ditg.TIME-10) + 1
296     if avg[3] > 0 and n[3] > 0:
297         com = ditg.createCmd_2(dst=ditg.src , port="10004" , tos=ditg .
SERV_3, nPkts=str(n[3]), avg=str(avg[3]))
298         print(com)
299         h3.cmd(com)
300         sum_out = sum_out + n[3]
301
302     # Serv 4 tx
303     n[4] = int(serv_4_tx[i])*F1 / ditg.SCALE + 1
304     avg[4] = n[4] / (ditg.TIME-10) + 1
305     if avg[4] > 0 and n[4] > 0:

```

```

306         com = ditg.createCmd_2(dst=ditg.dst, port="10005", tos=ditg.
SERV_4, nPkts=str(n[4]), avg=str(avg[4]))
307         print(com)
308         h1.cmd(com)
309         sum_in = sum_in + n[4]
310
311     # Serv 4 rx
312     n[4] = int(serv_4_rx[i])*F1 / ditg.SCALE + 1
313     avg[4] = n[4] / (ditg.TIME-10) + 1
314     if avg[4] > 0 and n[4] > 0:
315         com = ditg.createCmd_2(dst=ditg.src, port="10005", tos=ditg.
SERV_4, nPkts=str(n[4]), avg=str(avg[4]))
316         print(com)
317         h3.cmd(com)
318         sum_out = sum_out + n[4]
319
320     # Serv 5 tx
321     n[5] = int(serv_5_tx[i])*F2 / ditg.SCALE + 1
322     avg[5] = n[5] / (ditg.TIME-10) + 1
323     if avg[5] > 0 and n[5] > 0:
324         com = ditg.createCmd_2(dst=ditg.dst, port="10006", tos=ditg.
SERV_5, nPkts=str(n[5]), avg=str(avg[5]))
325         print(com)
326         h1.cmd(com)
327         sum_in = sum_in + n[5]
328
329     # Serv 5 rx
330     n[5] = int(serv_5_rx[i])*F2 / ditg.SCALE + 1
331     avg[5] = n[5] / (ditg.TIME-10) + 1
332     if avg[5] > 0 and n[5] > 0:
333         com = ditg.createCmd_2(dst=ditg.src, port="10006", tos=ditg.
SERV_5, nPkts=str(n[5]), avg=str(avg[5]))
334         print(com)
335         h3.cmd(com)
336         sum_out = sum_out + n[5]
337
338     # Serv 6 tx
339     n[6] = int(serv_6_tx[i])*F1 / ditg.SCALE + 1
340     avg[6] = n[6] / (ditg.TIME-10) + 1
341     if avg[6] > 0 and n[6] > 0:
342         com = ditg.createCmd_2(dst=ditg.dst, port="10007", tos=ditg.
SERV_6, nPkts=str(n[6]), avg=str(avg[6]))
343         print(com)
344         h1.cmd(com)
345         sum_in = sum_in + n[6]
346
347     # Serv 6 rx
348     n[6] = int(serv_6_rx[i])*F1 / ditg.SCALE + 1
349     avg[6] = n[6] / (ditg.TIME-10) + 1
350     if avg[6] > 0 and n[6] > 0:
351         com = ditg.createCmd_2(dst=ditg.src, port="10007", tos=ditg.
SERV_6, nPkts=str(n[6]), avg=str(avg[6]))
352         print(com)
353         h3.cmd(com)

```

```

354         sum_out = sum_out + n[6]
355
356
357     # Serv 7 tx
358     n[7] = int(serv_7_tx[i])*F1 / ditg.SCALE + 1
359     avg[7] = n[7] / (ditg.TIME-10) + 1
360     if avg[7] > 0 and n[7] > 0:
361         com = ditg.createCmd_2(dst=ditg.dst, port="10008", tos=ditg.
SERV_7, nPkts=str(n[7]), avg=str(avg[7]))
362         print(com)
363         h1.cmd(com)
364         sum_in = sum_in + n[7]
365
366     # Serv 7 rx
367     n[7] = int(serv_7_rx[i])*F1 / ditg.SCALE + 1
368     avg[7] = n[7] / (ditg.TIME-10) + 1
369     if avg[7] > 0 and n[7] > 0:
370         com = ditg.createCmd_2(dst=ditg.src, port="10008", tos=ditg.
SERV_7, nPkts=str(n[7]), avg=str(avg[7]))
371         print(com)
372         h3.cmd(com)
373         sum_out = sum_out + n[7]
374
375     j = j+1
376     i=i+1
377     if i % ditg.SIZE==0 and i!=0:
378         i=0
379         print i
380         print('Sum of Packets IN: ' + str(sum_in))
381         print('Sum of Packets OUT: ' + str(sum_out))
382
383     time.sleep(61)
384     check_time=False
385     while check_time==False:
386         now=datetime.datetime.now()
387         if now.minute%wait==0:
388             check_time=True
389             print "Time: " + str(now)
390             print 'Database Time: ' + str(time_values[i])
391         else:
392             time.sleep(1)
393         h1.cmd('kill %ITGSend')
394         h1.cmd('kill %ITGRecv')
395     CLI(net)
396     net.stop()
397
398 if __name__=='__main__':
399     setLogLevel('info')
400     myNetwork()

```

A.9 ditg.py

```
1 #!/usr/bin/python
2 import pandas as pd
3 import time
4
5 # Constants
6 # Value of Interval Time in second
7 TIME = 300
8 TIME_MS = TIME * 1000
9 # Scale factor for the packet rate. It will be equal to [ pkts / scale ]
10 # per second.
11 SCALE = 400
12 # CSV Entries
13 SIZE = 576
14 # Simulation Time in CSV hours
15 SIM = 720
16 # Simulation in number of intervals
17 SIM_N = SIM * 12
18 computername="jedi"
19 # CSV File
20 CSV = '/home/' + computername + '/Scrivania/RyuDatapathMonitor-master/CSV/
21 # ToS
22 SERV_0 = "0"
23 SERV_1 = "32"
24 SERV_2 = "72"
25 SERV_3 = "96"
26 SERV_4 = "136"
27 SERV_5 = "160"
28 SERV_6 = "192"
29 SERV_7 = "224"
30 # IDT_OPT
31 # constant
32 c_idt = "-C"
33 #poisson
34 p_idt = "-O"
35 #esponential
36 e_idt = "-E"
37
38 # PS_OPT
39 # constant
40 c_ps = "-c"
41 # poisson
42 p_ps = "-o"
43 # esponential
44 e_ps = "-e"
45
46 # default value for protocol and packet size
47 DEFAULT_P = "UDP"
48 DEFAULT_PS = "512"
49
```

```

50 # Host Ip
51 src = "10.0.0.11"
52 dst = "10.0.0.13"
53
54 # Type of distribution
55 choice_i = c_idt
56 choice_s = c_ps
57
58
59 # Cmd creation
60 def createCmd(src, dst, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
61     com = 'ITGManager ' + src + ' -a ' + dst + ' -b ' + tos + ' ' +
        choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t ' +
        str(TIME_MS-8000)
62     return com
63
64 # Cmd creation
65 def createCmd_2(dst, port, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
66     com = 'ITGSend -a ' + dst + ' -rp ' + str(port) + ' -b ' + tos + ' '
        + choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t
        ' + str(TIME_MS-10000) + ' &'
67     return com
68
69 # Cmd creation Iperf
70 def createCmd_3(dst, port, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
71     com = 'iperf3 -c ' + dst + ' -p ' + str(port) + ' -S ' + tos + ' ' +
        ' -k ' + str(nPkts) + ' &'
72     return com

```


Appendix B

Python Codes For Dedicated Hardware Network Devices

B.1 Traffic_Real_Hwd.py

```
2
3 from subprocess import call
4 import threading
5 import subprocess
6 import random
7 import os
8 import time
9 import datetime
10 import json
11 import sys
12 import ditg
13 import psutil
14 import SDL_DS1307
15
16
17 def f1():
18     IP_SRC='169.254.207.222'
19     IP_DST = "169.254.181.98"
20     os.system('sudo ifconfig eth0 '+IP_SRC+' netmask 255.255.0.0')
21     ds1307 = SDL_DS1307.SDL_DS1307(1, 0x68)
22     time.sleep(2)
23     now=ds1307.read_datetime()
24     str_time="" +str(now.year)+'-'+str(now.month)+'-'+str(now.day)+' '+
25     str(now.hour)+':'+str(now.minute)+':'+str(now.second)+'''
26     os.system('sudo date --set '+str_time)
27
28     print ('Csv Import')
29     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[0], skiprows
30     =[0]) # serv 0 tx
31     time_values = serv.values
32     serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[1], skiprows
33     =[0]) # serv 0 tx
34     serv_0_tx = serv.values
```

```

32 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[2], skiprows
33 =[0]) # serv 0 rx
34 serv_0_rx = serv.values
35 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[3], skiprows
36 =[0]) # serv 1 tx
37 serv_1_tx = serv.values
38 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[4], skiprows
39 =[0]) # serv 1 rx
40 serv_1_rx = serv.values
41 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[5], skiprows
42 =[0]) # serv 2 tx
43 serv_2_tx = serv.values
44 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[6], skiprows
45 =[0]) # serv 2 rx
46 serv_2_rx = serv.values
47 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[15], skiprows
48 =[0]) # serv 3 tx
49 serv_3_tx = serv.values
50 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[16], skiprows
51 =[0]) # serv 3 rx
52 serv_3_rx = serv.values
53 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[11], skiprows
54 =[0]) # serv 4 tx
55 serv_4_tx = serv.values
56 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[12], skiprows
57 =[0]) # serv 4 rx
58 serv_4_rx = serv.values
59 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[7], skiprows
60 =[0]) # serv 5 tx
61 serv_5_tx = serv.values
62 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[8], skiprows
63 =[0]) # serv 5 rx
64 serv_5_rx = serv.values
65 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[9], skiprows
66 =[0]) # serv 6 tx
67 serv_6_tx = serv.values
68 serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[10], skiprows
69 =[0]) # serv 6 rx
70 serv_6_rx = serv.values
serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[13], skiprows
serv_7_tx = serv.values
serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[14], skiprows
serv_7_rx = serv.values

i = 0
j = 0
### pkts
n = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
# pkts per second
avg = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
F0_max=2
F0=F0_max

```



```

71 F1=1
72 F2=1
73 print ('Wait for time alignment')
74 wait=ditg.TIME/60
75 check_time=False
76 while check_time==False:
77     now=datetime.datetime.now()
78     time.sleep(0.1)
79     try:
80         if now.minute%wait==0:
81             check_time=True
82             if len(str(now.minute))==1:
83                 starting_time=str(now.hour)+':0'+str(now.minute)
84             else:
85                 starting_time=str(now.hour)+':' +str(now.minute)
86             print (starting_time)
87             k=0
88             for index in time_values:
89                 if index==starting_time:
90                     i=k
91                     break
92             k=k+1
93         else:
94             time.sleep(0.5)
95     except:
96         time.sleep(0.1)
97 print ('Starting Time: '+str(time_values[i]))
98 while j < ditg.SIM_N:
99     try:
100         now=datetime.datetime.now()
101         if len(str(now.minute))==1:
102             starting_time=str(now.hour)+':0'+str(now.minute)
103         else:
104             starting_time=str(now.hour)+':' +str(now.minute)
105
106         if starting_time==time_values[1]:
107             print (starting_time)
108         else:
109             k=0
110             for index in time_values:
111                 if index==starting_time:
112                     i=k
113                     break
114             k=k+1
115     except:
116         time.sleep(0.1)
117     time.sleep(4)
118     # Sum of packets
119     sum_in = 0
120     sum_out = 0
121
122
123     # Serv 0 rx
124     n[0] = int(serv_0_rx[i])*F0 / ditg.SCALE + 1

```

```

125     avg[0] = n[0] / (ditg.TIME-10) + 1
126     if avg[0] > 0 and n[0] > 0:
127         com = ditg.createCmd_2(dst=IP_DST, port="10001", tos=ditg.
SERV_0, nPkts=str(n[0]), avg=str(avg[0]))
128         print(com)
129         os.popen(com)
130         sum_out = sum_out + n[0]
131
132     # Serv 1 rx
133     n[1] = int(serv_1_rx[i])*F0 / ditg.SCALE + 1
134     avg[1] = n[1] / (ditg.TIME-10) + 1
135     if avg[1] > 0 and n[1] > 0:
136         com = ditg.createCmd_2(dst=IP_DST, port="10002", tos=ditg.
SERV_1, nPkts=str(n[1]), avg=str(avg[1]))
137         print(com)
138         os.popen(com)
139         sum_out = sum_out + n[1]
140
141     # Serv 2 rx
142     n[2] = int(serv_2_rx[i])*F1 / ditg.SCALE + 1
143     avg[2] = n[2] / (ditg.TIME-10) + 1
144     if avg[2] > 0 and n[2] > 0:
145         com = ditg.createCmd_2(dst=IP_DST, port="10003", tos=ditg.
SERV_2, nPkts=str(n[2]), avg=str(avg[2]))
146         print(com)
147         os.popen(com)
148         sum_out = sum_out + n[2]
149
150     # Serv 3 rx
151     n[3] = int(serv_3_rx[i])*F0 / ditg.SCALE + 1
152     avg[3] = n[3] / (ditg.TIME-10) + 1
153     if avg[3] > 0 and n[3] > 0:
154         com = ditg.createCmd_2(dst=IP_DST, port="10004", tos=ditg.
SERV_3, nPkts=str(n[3]), avg=str(avg[3]))
155         print(com)
156         os.popen(com)
157         sum_out = sum_out + n[3]
158
159     # Serv 4 rx
160     n[4] = int(serv_4_rx[i])*F1 / ditg.SCALE + 1
161     avg[4] = n[4] / (ditg.TIME-10) + 1
162     if avg[4] > 0 and n[4] > 0:
163         com = ditg.createCmd_2(dst=IP_DST, port="10005", tos=ditg.
SERV_4, nPkts=str(n[4]), avg=str(avg[4]))
164         print(com)
165         os.popen(com)
166         sum_out = sum_out + n[4]
167
168     # Serv 5 rx
169     n[5] = int(serv_5_rx[i])*F2 / ditg.SCALE + 1
170     avg[5] = n[5] / (ditg.TIME-10) + 1
171     if avg[5] > 0 and n[5] > 0:
172         com = ditg.createCmd_2(dst=IP_DST, port="10006", tos=ditg.
SERV_5, nPkts=str(n[5]), avg=str(avg[5]))

```

```

173         print(com)
174         os.popen(com)
175         sum_out = sum_out + n[5]
176
177     # Serv 6 rx
178     n[6] = int(serv_6_rx[i])*F1 / ditg.SCALE + 1
179     avg[6] = n[6] / (ditg.TIME-10) + 1
180     if avg[6] > 0 and n[6] > 0:
181         com = ditg.createCmd_2(dst=IP_DST, port="10007", tos=ditg.
SERV_6, nPkts=str(n[6]), avg=str(avg[6]))
182         print(com)
183         os.popen(com)
184         sum_out = sum_out + n[6]
185
186     # Serv 7 rx
187     n[7] = int(serv_7_rx[i])*F1 / ditg.SCALE + 1
188     avg[7] = n[7] / (ditg.TIME-10) + 1
189     if avg[7] > 0 and n[7] > 0:
190         com = ditg.createCmd_2(dst=IP_DST, port="10008", tos=ditg.
SERV_7, nPkts=str(n[7]), avg=str(avg[7]))
191         print(com)
192         os.popen(com)
193         sum_out = sum_out + n[7]
194
195     j = j+1
196     i=i+1
197     if i % ditg.SIZE==0 and i!=0:
198         i=0
199         print(i)
200         print('Sum of Packets OUT: ' + str(sum_out))
201
202     ##Wait next minute to avoid another detection
203     check_time=False
204     while check_time==False:
205         now=datetime.datetime.now()
206         try:
207             if (now.minute== 4 or now.minute==17 or now.minute==31
or now.minute==41 or now.minute==54) and now.second==0:
208                 now=ds1307.read_datetime()
209                 str_time="" + str(now.year) + '-' + str(now.month) + '-' +
str(now.day) + ' ' + str(now.hour) + ':' + str(now.minute) + ':' + str(now.
second) + ""
210                 os.system('sudo date --set ' + str_time)
211                 now=datetime.datetime.now()
212                 if now.minute%wait==1:
213                     check_time=True
214             else:
215                 time.sleep(1)
216         except:
217             time.sleep(0.1)
218
219     check_time=False
220     while check_time==False:
221         now=datetime.datetime.now()

```

```

222         try:
223             if (now.minute== 4 or now.minute==17 or now.minute==31
or now.minute==41 or now.minute==54) and now.second==0:
224                 now=ds1307.read_datetime()
225                 str_time=""'+str(now.year)+'-'+str(now.month)+'-'+
str(now.day)+' '+str(now.hour)+':'+str(now.minute)+':'+str(now.
second)+'"'
226                 os.system('sudo date --set '+str_time)
227                 now=datetime.datetime.now()
228                 if now.minute%wait==0:
229                     check_time=True
230                     print ("Time: "+str(now))
231                     print ('Database Time: '+str(time_values[i]))
232                 else:
233                     time.sleep(1)
234             except:
235                 time.sleep(0.1)
236         try:
237
238             cmd = "pidof ITGRecv"
239             PID = subprocess.check_output(cmd, shell=True).decode("utf-8
")
240
241             print ("pidof ITGRecv: "+str(PID))
242             os.popen('sudo kill -9 '+str(PID))
243             cmd = "pidof ITGSend"
244             PID = subprocess.check_output(cmd, shell=True).decode("utf-8
")
245
246             print ("pidof ITGSend: "+str(PID))
247             os.popen('sudo kill -9 '+str(PID))
248         except:
249             time.sleep(0.1)
250
251 def f2():
252     while True:
253         try:
254             print("Start ITGRecv")
255             os.popen('ITGRecv')
256         except:
257             time.sleep(1)
258
259 t1 = threading.Thread(target=f1, args=())
260 t2 = threading.Thread(target=f2, args=())
261
262 #Started the threads
263 t1.start()
264 time.sleep(4)
265 t2.start()
266
267 #Joined the threads
268 t1.join()
269 t2.join()

```

B.2 Start_ITGRecv.py

```
2 from subprocess import call
3 import threading
4 import subprocess
5 import random
6 import os
7 import time
8 import datetime
9 import json
10 import sys
11 import ditg
12
13 while True:
14     try:
15         print("Start ITGRecv")
16         os.popen('ITGRecv')
17     except:
18         time.sleep(1)
```

B.3 ditg.py

```
2 #!/usr/bin/python
3
4 import pandas as pd
5 import time
6
7 # Constants
8 # Value of Interval Time in second
9 TIME = 300
10 TIME_MS = TIME * 1000
11 # Scale factor for the packet rate. It will be equal to [ pkts / scale ]
12     per second.
13 SCALE = 400
14 # CSV Entries
15 SIZE = 576
16 # Simulation Time in CSV hours
17 SIM = 720
18 # Simulation in number of intervals
19 SIM_N = SIM * 12
20 computername="pi"
21 # CSV File
22 CSV = '/home/' + computername + '/Desktop/Hardware_Interface/CSV/
23     vlan_interfaccia1_DOS.csv'
24
25 # ToS
26 SERV_0 = "0"
27 SERV_1 = "32"
28 SERV_2 = "72"
29 SERV_3 = "96"
30 SERV_4 = "136"
31 SERV_5 = "160"
```

```

29 SERV_6 = "192"
30 SERV_7 = "224"
31
32 # IDT_OPT
33 # constant
34 c_idt = "-C"
35 #poisson
36 p_idt = "-O"
37 #esponential
38 e_idt ="-E"
39
40 # PS_OPT
41 # constant
42 c_ps = "-c"
43 # poisson
44 p_ps = "-o"
45 # esponential
46 e_ps ="-e"
47
48 # default value for protocol and packet size
49 DEFAULT_P = "UDP"
50 DEFAULT_PS = "512"
51
52 # Host Ip
53 dst = "169.254.207.100"
54
55 # Type of distribution
56 choice_i = c_idt
57 choice_s = c_ps
58
59
60 # Cmd creation
61 def createCmd(src , dst , tos , nPkts , avg , protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
62     com = 'ITGManager ' + src + ' -a ' + dst + ' -b ' + tos + ' ' +
        choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t ' +
        str(TIME_MS-8000)
63     return com
64
65 # Cmd creation
66 def createCmd_2(dst , port , tos , nPkts , avg , protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
67     com = 'ITGSend -a ' + dst + ' -rp ' + str(port) + ' -b ' + tos + ' '
        + choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t
        ' + str(TIME_MS-10000)+ ' &'
68     return com
69
70 # Cmd creation Iperf
71 def createCmd_3(dst , port , tos , nPkts , avg , protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
72     com = 'iperf3 -c ' + dst + ' -p ' + str(port) + ' -S ' + tos + ' ' +
        ' -k ' + str(nPkts) + ' &'
73     return com

```

B.4 Set_Queue.py

```
2 from subprocess import call
3 import threading
4 import subprocess
5 import random
6 import os
7 import time
8 import datetime
9 import json
10 import sys
11 import ditg
12
13 from Controller_commands import *
14
15 max_rate_queue=100#Mbps
16 max_rate_queue=max_rate_queue*1000000
17 Default=str(max_rate_queue*20/100)#20%
18 Premium=str(max_rate_queue*80/100)#80%
19 Gold=str(max_rate_queue*100/100)#100%
20
21 def set_queue_eth2():
22     NET = get_switchis()
23     if NET != "NO NET" and NET!="[, ]":
24         i=1
25         while i<NET.find("]"):
26             mom_NET=NET[i:]
27             datapath=NET[i:i+mom_NET.find(",")]
28             i=i+mom_NET.find(",")+2
29             port_id = switch_ports_name(datapath)
30             time.sleep(0.2)
31             i=1
32             while i<NET.find("]"):
33                 mom_NET=NET[i:]
34                 datapath=NET[i:i+mom_NET.find(",")]
35                 i=i+mom_NET.find(",")+2
36                 port_id = switch_ports_name(datapath)
37                 ovsdb_addr(datapath)
38
39                 print(port_id)
40                 IP_Flag=True
41                 for index in range(0,len(port_id)):
42                     if port_id[index]=="eth2" or port_id[index]=="eth1":
43                         print "Port_ID: "+port_id[index]
44                         port = port_id[index][port_id[index].find("h")+1:]
45                         if port_id[index]=="eth2":
46                             set_queue(datapath, port_id[index], str(
max_rate_queue), {"max_rate\ ": \"+Default+"\"}, {"max_rate\ ": \"+Premium+"\"}, {"min_rate\ ": \"+Gold+"\"})
47                             IP_Destination="169.254.181.98"
48                             set_Telecom_queue(datapath, port, IP_Flag,
IP_Destination)
49
```

```

50 try:
51     os.popen("sudo -S curl -X DELETE http://localhost:8080/qos/queue
/0000000000000002", 'w').write("Ao70pa45")
52     print "\n"
53     set_queue_eth2()
54 except:
55     print "ERROR"

```

B.5 SendTime.py

```

2  #!/usr/bin/python
3  import serial
4  import time
5  import datetime
6  import os
7
8  os.popen("sudo chmod a+rw /dev/ttyACM0", 'w').write("Ao70pa45")
9
10
11 def read_all(port, chunk_size=200):
12     """Read all characters on the serial port and return them."""
13     if not port.timeout:
14         raise TypeError('Port needs to have a timeout set!')
15
16     read_buffer = b''
17
18     while True:
19         # Read in chunks. Each chunk will wait as long as specified by
20         # timeout. Increase chunk_size to fail quicker
21         byte_chunk = port.read(size=chunk_size)
22         read_buffer += byte_chunk
23         if not len(byte_chunk) == chunk_size:
24             break
25
26     return read_buffer
27
28 # 'COM3'
29 ser = serial.Serial(
30     port = '/dev/ttyACM0',
31     baudrate = 115200,
32     parity = serial.PARITY_NONE,
33     stopbits = serial.STOPBITS_ONE,
34     bytesize = serial.EIGHTBITS,
35     timeout=0.5, # IMPORTANT, can be lower or higher
36     inter_byte_timeout=0.1 # Alternative
37 )
38 time.sleep(5)
39 flag = 0;
40 first_loop=0;
41 bufsize=0;
42 while True:

```



```

43     ts = datetime.datetime.now();
44
45     sec_mom=ts.second;
46     minute_mom=ts.minute;
47     hour_mom=ts.hour;
48     DAY_mom=ts.day;
49     MONTH_mom=ts.month;
50     YEAR=str(ts.year);
51
52     if sec_mom<10:
53         sec='0'+str(ts.second);
54     else:
55         sec=str(ts.second);
56     if minute_mom<10:
57         minute='0'+str(ts.minute);
58     else:
59         minute=str(ts.minute);
60     if hour_mom<10:
61         hour='0'+str(ts.hour);
62     else:
63         hour=str(ts.hour);
64     if DAY_mom<10:
65         DAY='0'+str(ts.day);
66     else:
67         DAY=str(ts.day);
68     if MONTH_mom<10:
69         MONTH='0'+str(ts.month);
70     else:
71         MONTH=str(ts.month);
72
73     DATA=YEAR+' '+MONTH+' '+DAY+' '+hour+' '+minute+' '+sec;
74
75     if minute_mom%13==0 and sec_mom==0:
76         flag=0;
77     if flag==0:
78     if first_loop==0:
79         print("Time aligned at:")
80         print(DATA)
81         first_loop=1
82
83     ser.write(DATA.encode()) #Send data to arduino. Activate
arduino read pin and write to serial
84     time.sleep(2)
85     byteData = read_all(ser)
86     if byteData.decode("utf-8")==="1":
87         flag=1;
88     else:
89         print("ERROR--->resend data")
90         flag=0;
91     time.sleep(1)
92     else:
93         time.sleep(0.2)

```

B.6 ReadTime.ino

```
2 #include <Wire.h>
3 #include <TimeLib.h>
4 #include <DS1307RTC.h>
5
6 const char *monthName[12] = {
7     "Jan", "Feb", "Mar", "Apr", "May", "Jun",
8     "Jul", "Aug", "Sep", "Oct", "Nov", "Dec"
9 };
10
11 tmElements_t tm;
12
13 char inByte=0;
14 int lenbuffer=19;
15 byte bufferDATA[19];
16
17 String myString;
18 String Hour;
19 String Min;
20 String Sec;
21 String Day;
22 String Month;
23 String Year;
24
25 void setup() {
26     Serial.begin(115200);
27     pinMode(LED_BUILTIN, OUTPUT);
28     digitalWrite(LED_BUILTIN, LOW);
29     while (!Serial) {
30         ; // wait for serial port to connect. Needed for
native USB
31     }
32 }
33
34 void loop() {
35
36     String DATA;
37     if (Serial.available() > 0) //Waiting for request
38     {
39         Serial.readBytes(bufferDATA, lenbuffer);
40         myString = String((char *)bufferDATA);
41         Hour=myString.substring(11, 13);
42         Min=myString.substring(14, 16);
```

```
43     Sec=myString.substring(17, 19);
44     Day=myString.substring(8, 10);
45     Month=myString.substring(5, 7);
46     Year=myString.substring(0, 4);
47
48     tm.Hour = Hour.toInt();
49     tm.Minute = Min.toInt();
50     tm.Second = Sec.toInt();
51     tm.Day = Day.toInt();
52     tm.Month = Month.toInt();
53     tm.Year = CalendarYrToTm(Year.toInt());
54     RTC.write(tm);
55     Serial.print("1");
56     delay(1000);
57 }
58
59 }
```