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 retrive 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.

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 enqueuing 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 of 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 techinques 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 Bird 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 always 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.

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 [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].

Deriving accurate dynamical models of communication networks that can be directly used for optimal control by the exploitation of historical network data is still a challenging and actual problem [26, 27, 28, 29, 30].

Recent advances in computing technologies such as Graphics Processing Unit and Tensor Processing Unit provide a good opportunity to apply promising machine learning techniques (e.g., deep neural networks) in the network field [31, 32]. Data is the key to the data-driven machine learning algorithm: the centralized SDN controller has a global network view, and is able to collect various network data. 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.

The manuscript is organized as follows: a background knowledge about SDN and Machine learning has been introduced in Section 1.1 and in Section 1.2 respectively; in Section 2.1 the network emulation environment has been illustrated; in Section 2.2 the model identification technique and its embedding in a MPC problem formulation solvable via Quadratic Programming (QP) has been described; in Section 2.3 the prediction accuracy and control performance validation using the proposed emulation environment has been provided.

Chapter 1

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].

1.1 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 1.1. In the following, we give a brief description of these planes and their interactions.

1.1.1 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

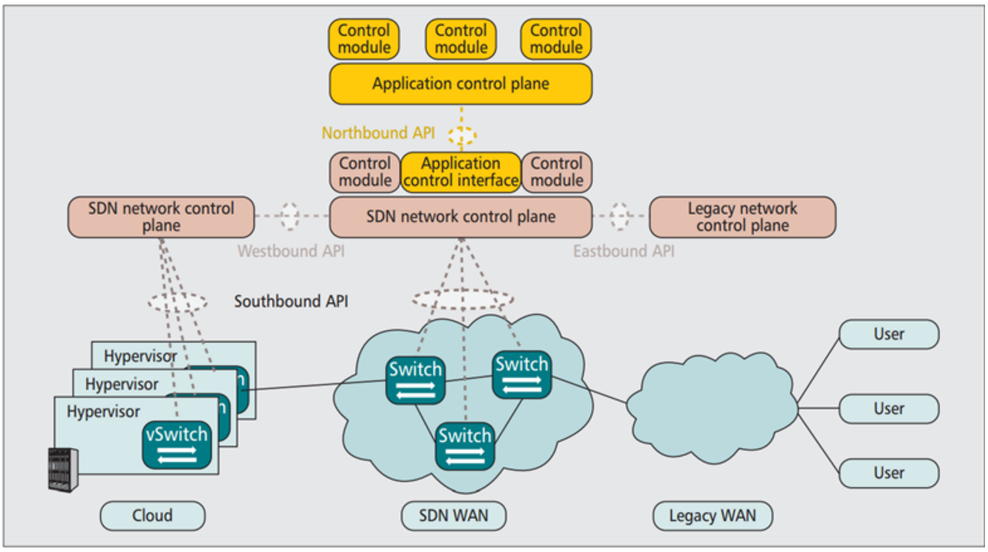


Figure 1.1: The high-level SDN architecture proposed by ONF.

[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).

1.1.2 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 responsable 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.

1.1.3 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 1.2 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

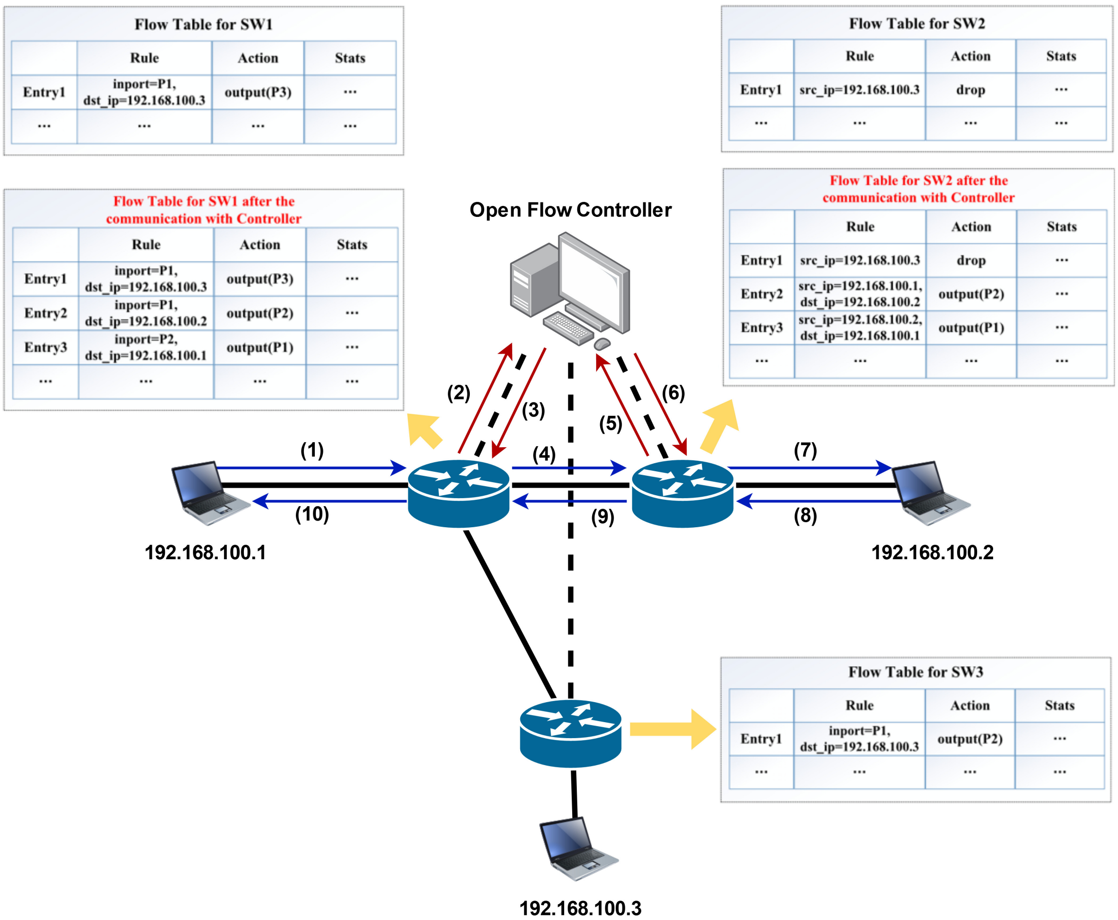


Figure 1.2: Example of OpenFlow-based SDN network.

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.

1.2 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 1.3 is briefly explained with some examples. For a more insightful discussion on machine learning theory, please refer to [108, 109, 110].

1.2.1 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

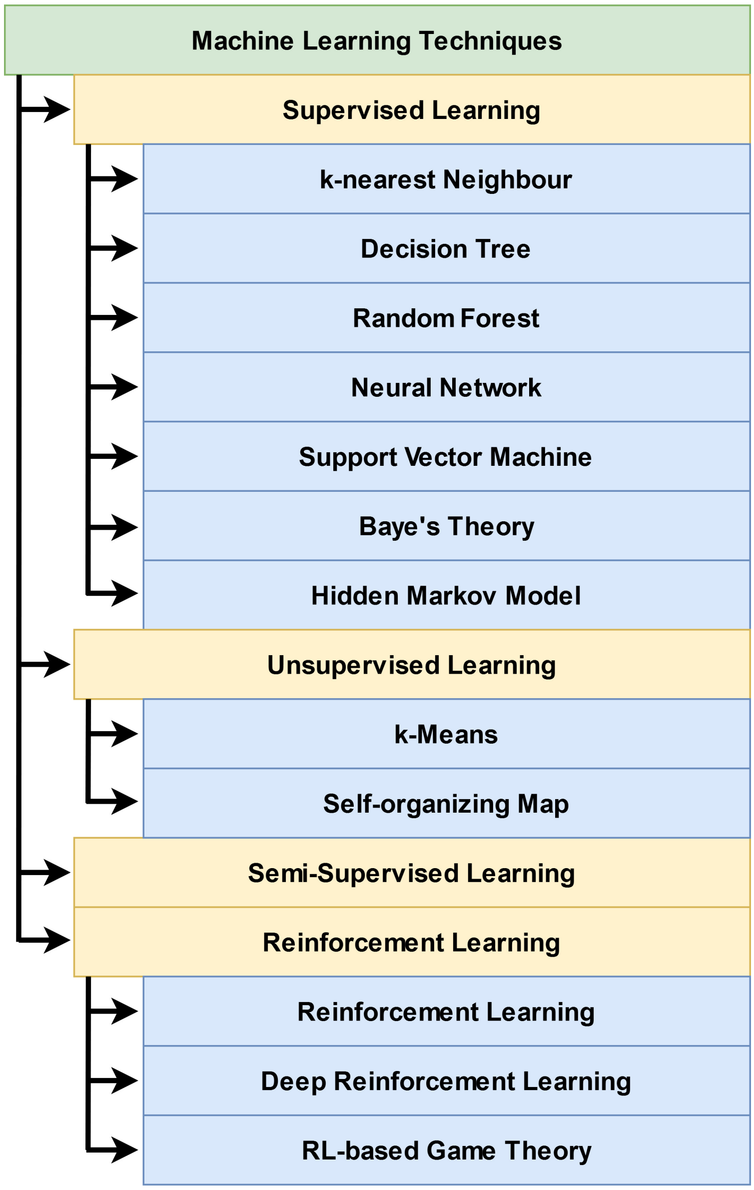


Figure 1.3: Common machine learning algorithms.

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) Regresstion 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 1.4 the most basic NN with three layers has been shown. An input has m features (i.e., $X_1, X_2, ..., X_m$) and the input can be assigned to n possible classes (i.e., $Y_1, Y_2, ..., Y_n$). Also, W^1_{ij} denotes the variable link weight between the ith neuron of layer l and the jth neuron of layer $l + 1$, and ak^l denotes the activation function of the kth 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

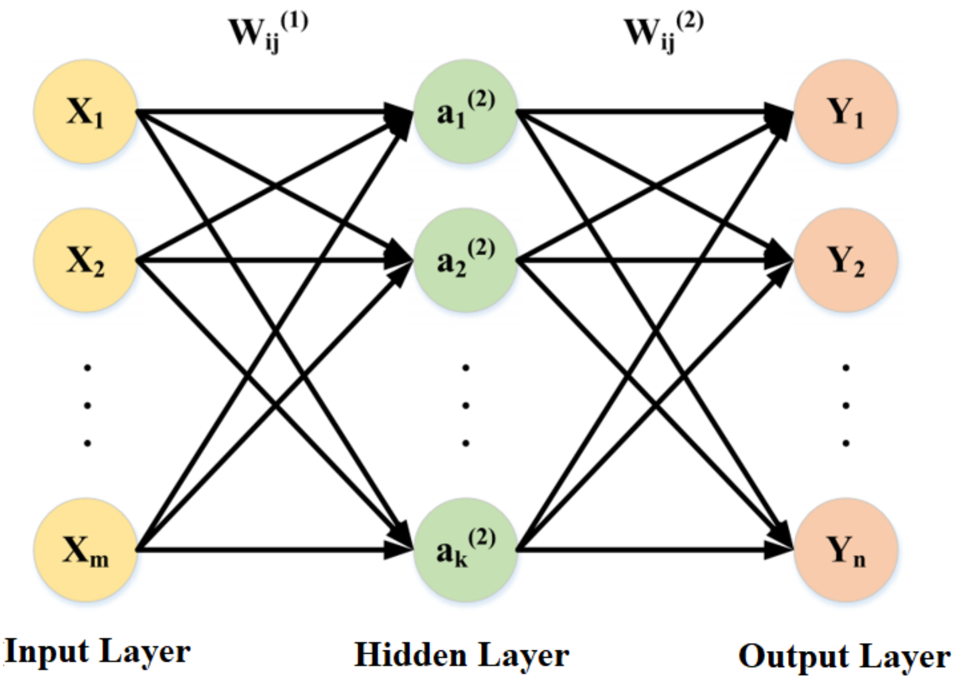


Figure 1.4: A basic neural network with three layers: an input layer, a hidden layer and an output layer.

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 neurondependent 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.

1.2.2 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).

1.2.3 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 difficults 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.

1.2.4 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 $st + 1$. 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 $A(\pi : S \longrightarrow A)$ 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 2

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.

2.1 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 2.1, which aims to represent a portion of a larger network where a bottleneck occurs. More precisely, we consider a switch $s0$ with one input port and one output port, and a remote controller [62, 68] that dynamically manages the configuration of the queues of $s0$. The input of $s0$ 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

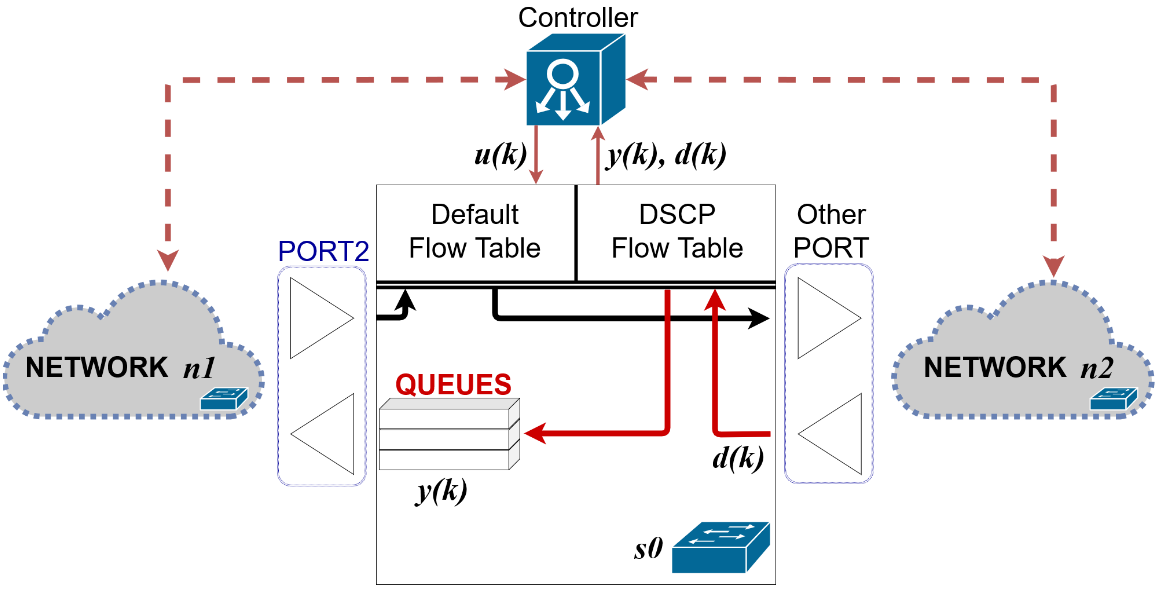


Figure 2.1: Mininet emulated network architecture.

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

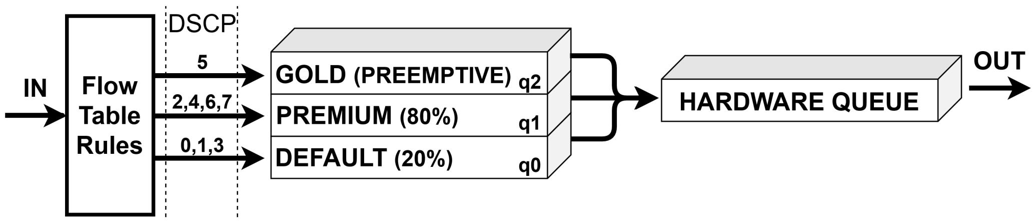


Figure 2.2: Static queues rate with routed packets relative to DSCP.

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 $d_1(k), \ldots, d_8(k)$ consist of the number of packets incoming in the switch $s0$ 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 $s0$ 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 2.2. To this aim we defined 3 queues in $s0$ 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 $u_1(k) = 20$*MB/s*$, \forall k$; the packets with values 2, 4, 6 and 7 (Premium queue) are routed on queue 1, with maximum rate $u_2(k) = 80$*MB/s*$, \forall k$; the packets with value 5 (Gold queue) are routed on queue 2, with minimum rate $u_3(k) = 100$*MB/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 2.3, 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 2.2.

2.2 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:

$$x(k+j+1) = A'_{\sigma_j(x(k),d(k))}x(k) + \sum_{\alpha=0}^{j} B'_{\sigma_j(x(k),d(k)),\alpha}u(k+\alpha) + f'_{\sigma_j(x(k),d(k))}, \tag{2.1}$$

$j = 0, \dots, N-1$, 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 $\sigma_j : \mathbb{R}^{n_x+10} \to \mathcal{M} \subset \mathbb{N}$ 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 (2.1) to setup the following problem, which can be solved using standard Quadratic Programming (QP) solvers:

Problem 1

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

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.

2.2.1 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) $R_1, R_2, \cdots, R_\nu$. In each partition $y(k)$

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

$$\hat{y}_i = \frac{\sum\limits_{\{k|(x_1(k),\ldots,x_\eta(k))\in R_i\}} y(k)}{|R_i|} \tag{2.2}$$

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 refered to [149, 150].

2.2.2 Switching ARX (SARX) model identification via RT

To derive a model as in (2.1), 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 $\{\mathcal{T}_{\iota,j}\}, \ \iota = 1, 2, 3, \ j = 0, \ldots, N-1$, 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 (2.2). 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 (2.7). 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

$$x_\iota(k+j+1) = A'_{\iota,i_j} x(k) + \sum_{\alpha=0}^{j} B'_{\iota,i_j,\alpha} u(k+\alpha) + f'_{\iota,i_j}, \tag{2.3}$$

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

$$B'_{\iota,i_j,\alpha} = \begin{bmatrix} b_{1,\alpha} & b_{2,\alpha} & b_{3,\alpha} \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix}, \ \alpha < j, \ B'_{\iota,i_j,j} = \begin{bmatrix} b_{1,\alpha} & b_{2,\alpha} & b_{3,\alpha} \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 0 & 0 \end{bmatrix}, \ f'_{\iota,i_j} = \begin{bmatrix} f \\ 0 \\ \vdots \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \tag{2.4}$$

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

$$\begin{aligned} \underset{\xi_{\iota,i_j}}{\textit{minimize}} \quad & \| \Lambda_{\iota,i_j} \xi_{\iota,i_j} - \lambda_{\iota,i_j} \|_2^2 \\ \textit{subject to} \ & f_{\min} \leq f \leq f_{\max} \\ & a_{\min} \leq a_\jmath \leq a_{\max} \\ & b_{\min} \leq b_{\iota,\alpha} \leq b_{\max}, \end{aligned} \tag{2.5}$$

where ξ_{ι,i_j}, λ_{ι,i_j}, and Λ_{ι,i_j} contain respectively the parameters of matrices in (2.4), the predictions $x_\iota(k+j+1)$, and the current measurements of $x(k)$ and $u(k+\alpha)$. Linear inequalities (2.5) are used to constrain elements in ξ_{ι,i_j} to take into account physical system constraints and improve prediction accuracy. Model (2.3) can be easily compacted in the following form taking into account all the states $\iota = 1, 2, 3$:

$$x(k+j+1) = A'_{i_j} x(k) + \sum_{\alpha=0}^{j} B'_{i_j,\alpha} u(k+\alpha) + f'_{i_j}. \tag{2.6}$$

In particular, with the specific choice of $\delta_u = 0$ model (2.1) can be rewritten in the following state-space formulation

$$x(k+j+1) = A_{\sigma_j(x(k),\mathbf{u}^-(k),d(k))} x(k+j) + B_{\sigma_j(x(k),\mathbf{u}^-(k),d(k))} u(k+j) + f_{\sigma_j(x(k),\mathbf{u}^-(k),d(k))}, \tag{2.7}$$

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 $\sigma_j : \mathbb{R}^{3(\delta_y+1)+3\delta+10} \to \mathcal{M} \subset \mathbb{N}$. Thanks to this new formulation the following proposition shows that model (2.6) is equivalent to model (2.7) 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}, $\alpha = 0, \ldots, j$, $j = 0, \ldots, N-1$, be given. If A'_{i_j} is invertible for $j = 0, \ldots, N-1$, 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 $i_0, \ldots, i_{N-1}$ and any control sequence $u(k), \ldots, u(k+N-1)$, then $\bar{x}(k+j+1) = x(k+j+1)$, $\forall j = 0, \ldots, N-1$.

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.

2.2.3 SARX model identification via RF

RF-based models can be constructed exploiting the RT-based formulation: in particular, let us consider $3N$ RFs $\mathcal{F}_{\iota,j}$, $\iota = 1, 2, 3,\ j = 0, \ldots, N-1$. 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 (2.4) 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 (2.9) can be obtained by averaging parameters a_*, b_* and f, $\forall \tau = 1, \ldots, |\mathcal{F}_{\iota,j}|$, i.e.

$$\tilde{\xi}_{\iota,j} = \frac{\sum_{\tau=1}^{|\mathcal{F}_{\iota,j}|} \tilde{\xi}_{\iota,j,i_\tau}}{|\mathcal{F}_{\iota,j}|}, \tag{2.8}$$

over all the trees of forest $\mathcal{F}_{\iota,j}$. At this point, starting from (2.3), it can be easily construct the following model, as in (2.6) to be used in the MPC formulation by combining for $\iota = 1, 2, 3$ the matrices in (2.4) coming either from the RTs or from the RFs:

$$x(k + j + 1) = A'_{i_j} x(k) + \sum_{\alpha=0}^{j} B'_{i_j,\alpha} u(k + \alpha) + f'_{i_j}. \tag{2.9}$$

2.2.4 MPC problem formulation.

Model (2.9) is used to formalize Problem 1 according to the SDN priority queueing problem:

Problem 3

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

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 $k + j$; $\Delta u_\iota^{\min}$ and $\Delta u_\iota^{\max}$ 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; $u_\iota^{\min}$ and $u_\iota^{\max}$ 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 (2.9) narrowing down the leaves of the trees, for $j = 0, \ldots, N - 1$, solve Problem (3), and finally apply only the first input of the optimal sequence $\mathbf{u}^*$ found, i.e. $u(k) = u_0^*$.

2.2.5 Disturbance forecast

The knowledge at each time k of the future input traffic $(d(k+1), \ldots, d(k+N-1))$ 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 $\mathcal{F}^{d}_{\iota,j},\ \iota = 1, \ldots, 8,\ j = 0, \ldots, N-1$ 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 $\mathcal{X} = \{(x(k), u(k), d(k), \ldots, d(k+N-1))\}_{k=1}^{\ell}$ for the training phase, and considering a switching signal in (2.7) given by $\sigma_j(k) = \sigma_j(x(k), \mathbf{u}^{-}(k), d(k), \hat{d}(k+1), \ldots, \hat{d}(k+j)), \forall j = 0, \ldots, N-1$, i.e. also depending at time k on the future input traffic.

2.3 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 $d_1(k), \ldots, d_8(k)$, 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 2.2 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 2.1: even thought 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].

2.3.1 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 2.3 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 2.4 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.

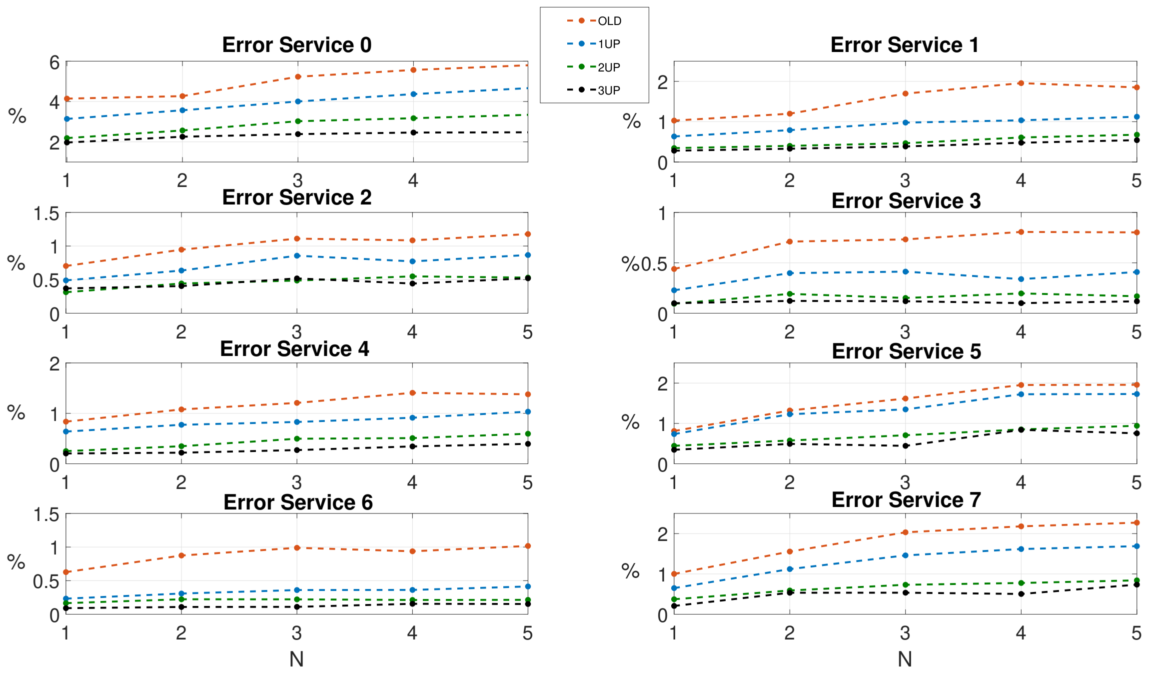


Figure 2.3: NRMSE of the disturbance predictive model over a time horizon of $N = 5$.

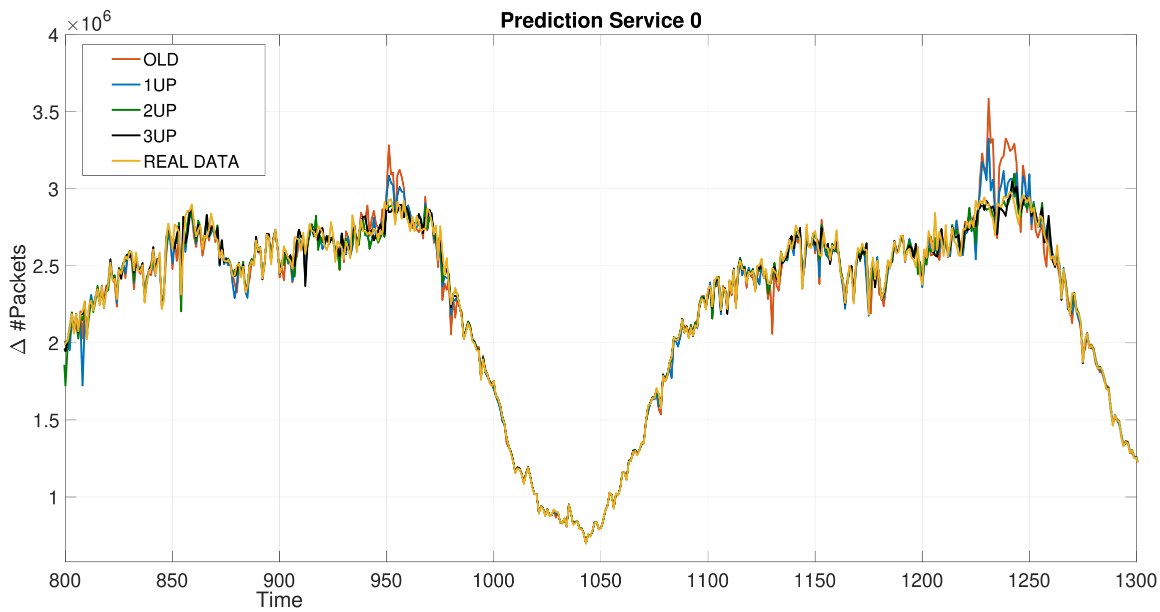


Figure 2.4: Comparison between the real traffic (YELLOW LINE) and the traffic prediction for the different models for Service 0.

2.3.2 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 2.2 and Problem 2) are summarized in Table 2.1. In particular, the regressive terms (δ_d, δ_x, δ_u) and the minimum number of samples

Table 2.1: 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
$\lvert\mathcal{F}_{ij}\rvert$	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 depper 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*).

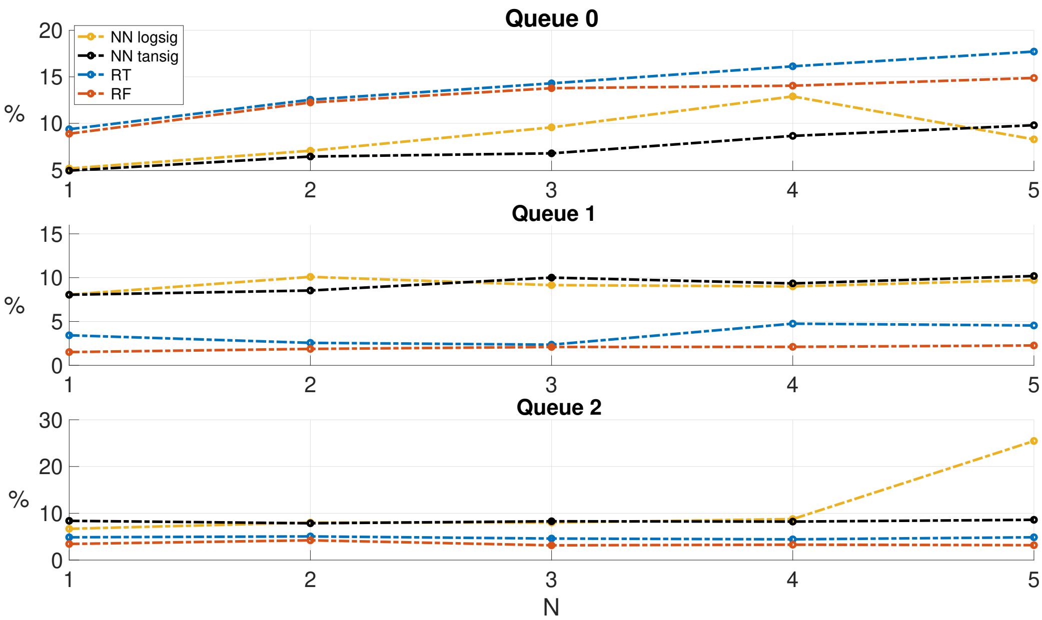


Figure 2.5: NRMSE, up to $N = 5$ and for each priority class, for RT (blue), RF (red), NN with sigmoids as activation function (yellow) and NN with hyperbolic tangent as activation function (black).

As a metric of the prediction accuracy we compared in Figure 2.5 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 thought 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 2.6), we noticed a peculiar regular grid pattern that can be very well approximated 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,

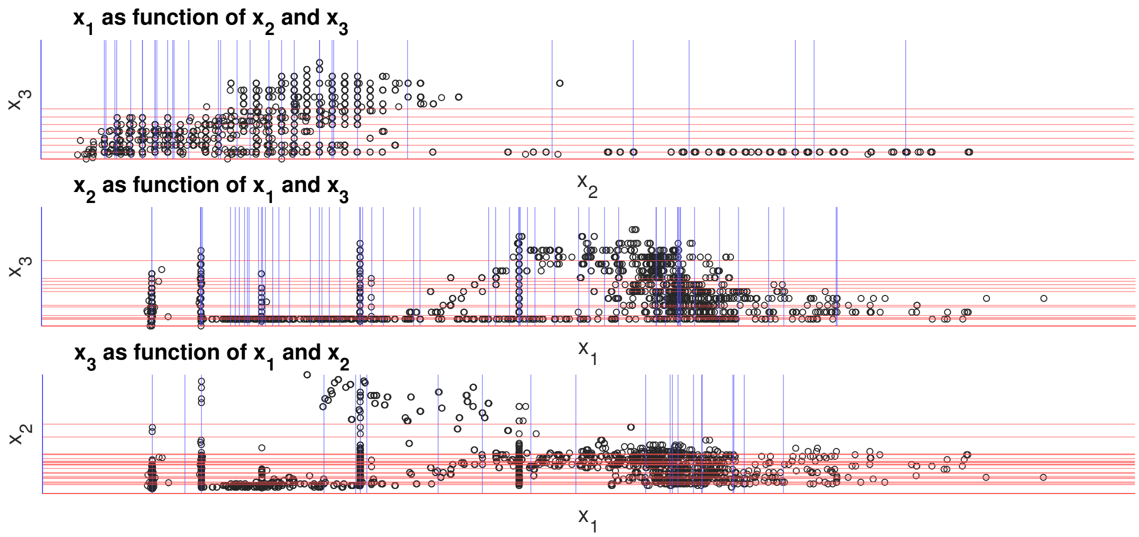


Figure 2.6: Grid pattern emerged from dataset distribution.

even thought 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 weitghts 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 2.7 and Figure 2.8 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*

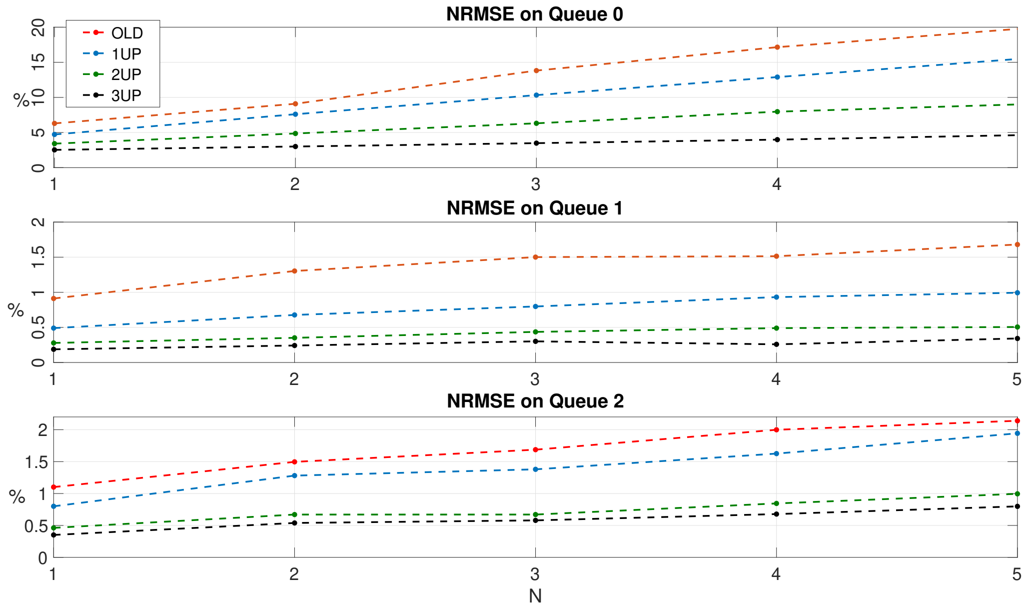


Figure 2.7: NRMSE of the queues output predictive model over a time horizon of $N = 5$, without knowledge of the future disturbances

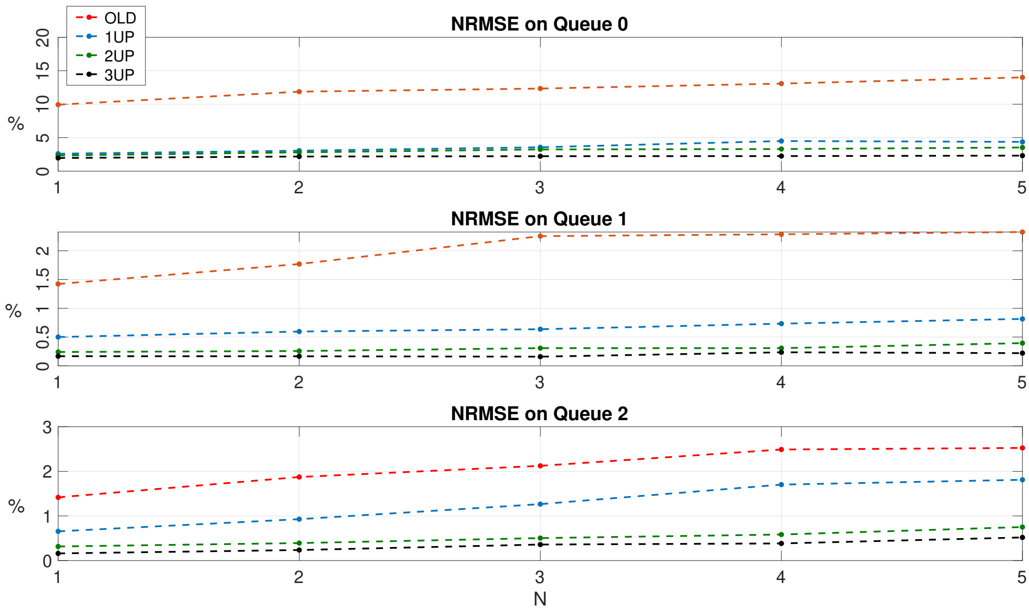


Figure 2.8: NRMSE of the queues output predictive model over a time horizon of $N = 5$, with knowledge of the 4-steps future disturbances

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.*

2.3.3 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 $Q = diag(1, 10^4, 10)$ 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 2.2. In what follows we validate the control

Table 2.2: Constraints in Problem 3

Parameters	Value	Parameters	Values
$\Delta u_1^{\min}$	1	$\Delta u_1^{\max}$	30
$\Delta u_2^{\min}$	20	$\Delta u_2^{\max}$	30
$\Delta u_3^{\min}$	20	$\Delta u_3^{\max}$	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.

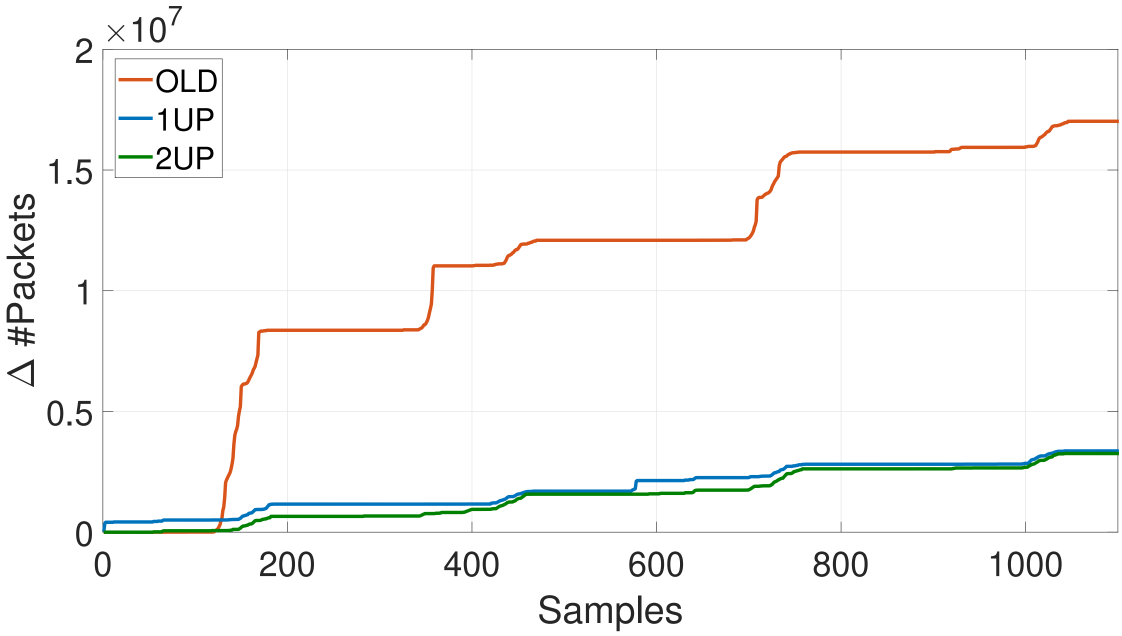


Figure 2.9: Cumulative Packet Losses without knowledge of the future disturbance.

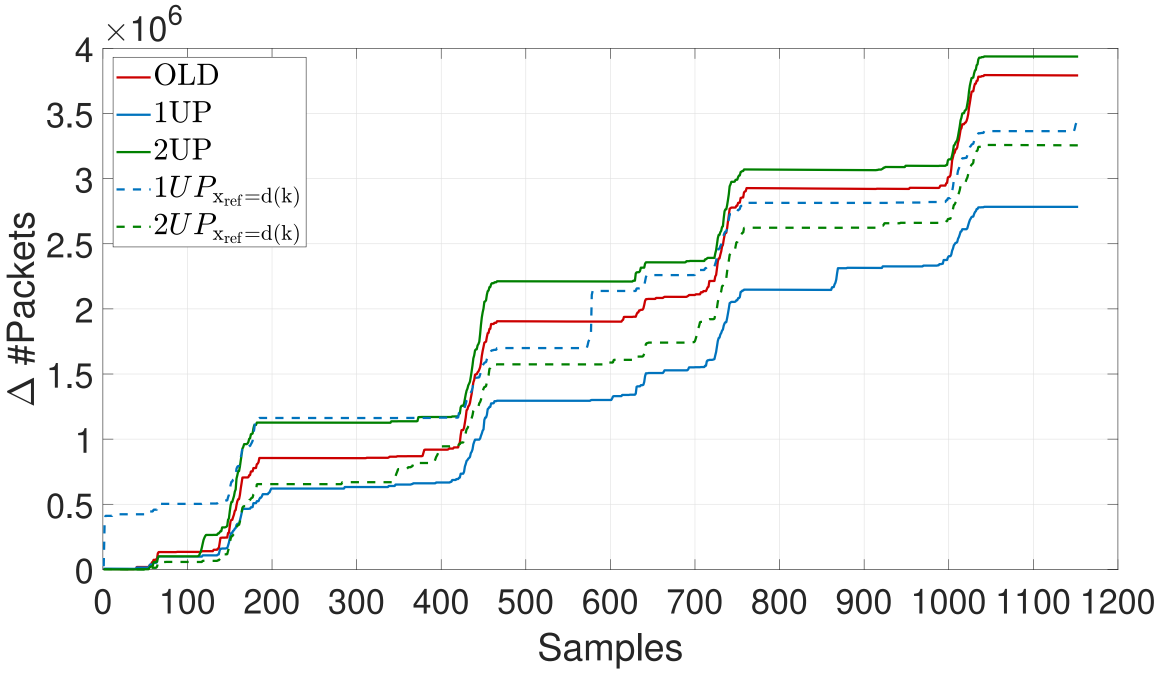
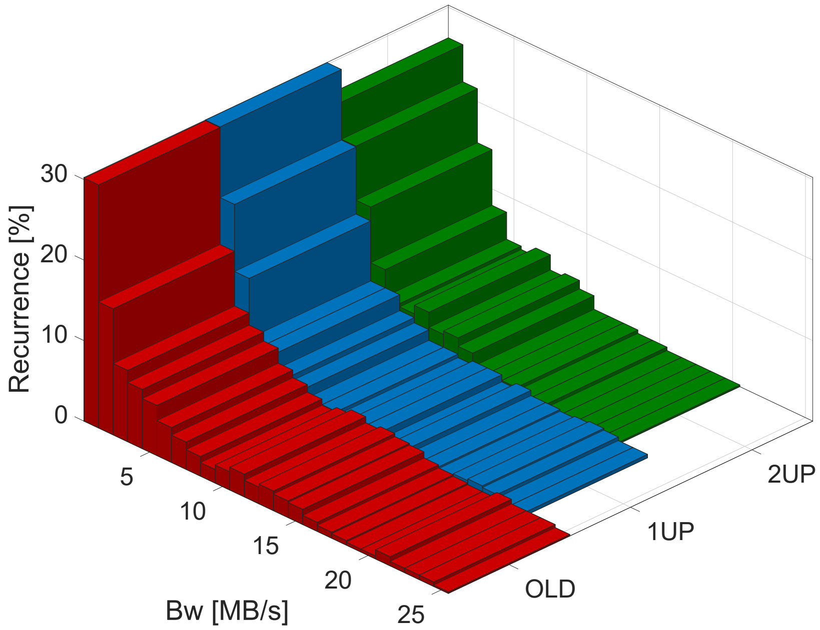


Figure 2.10: Comparison between Cumulative Packet Losses with (solid lines) and without (dashed lines) knowledge of the future disturbance.

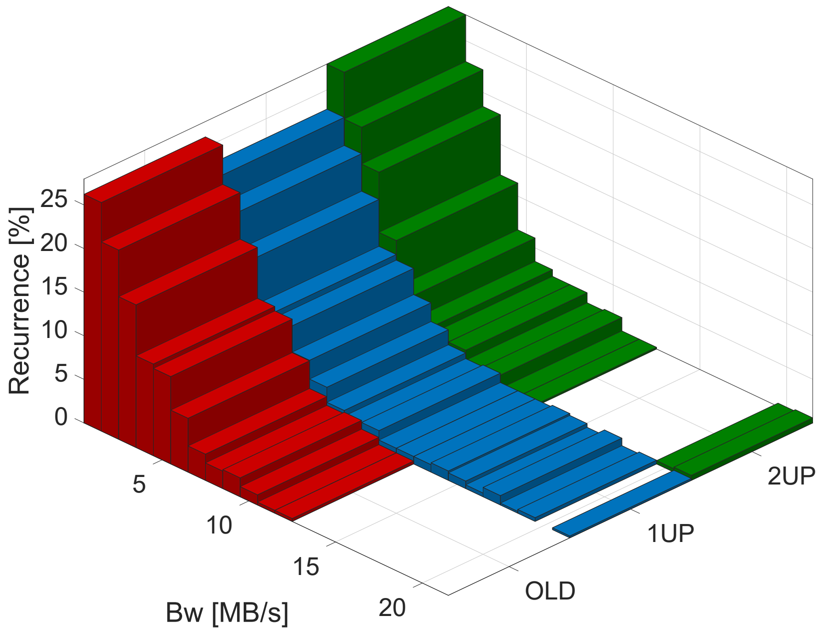
Figures 2.9 and 2.10 plot the cumulative packet losses respectively without and with knowledge of the future disturbances. The packet loss rate when the control is performed exploiting the OLD model and without disturbance forecast is around 123% larger than all other cases (and, of course, incomparably 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 2.11 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 2.12 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 thought 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.



(a)



(b)

Figure 2.11: Bandwidth saving comparison without (a) and with (b) knowledge of the future disturbances.

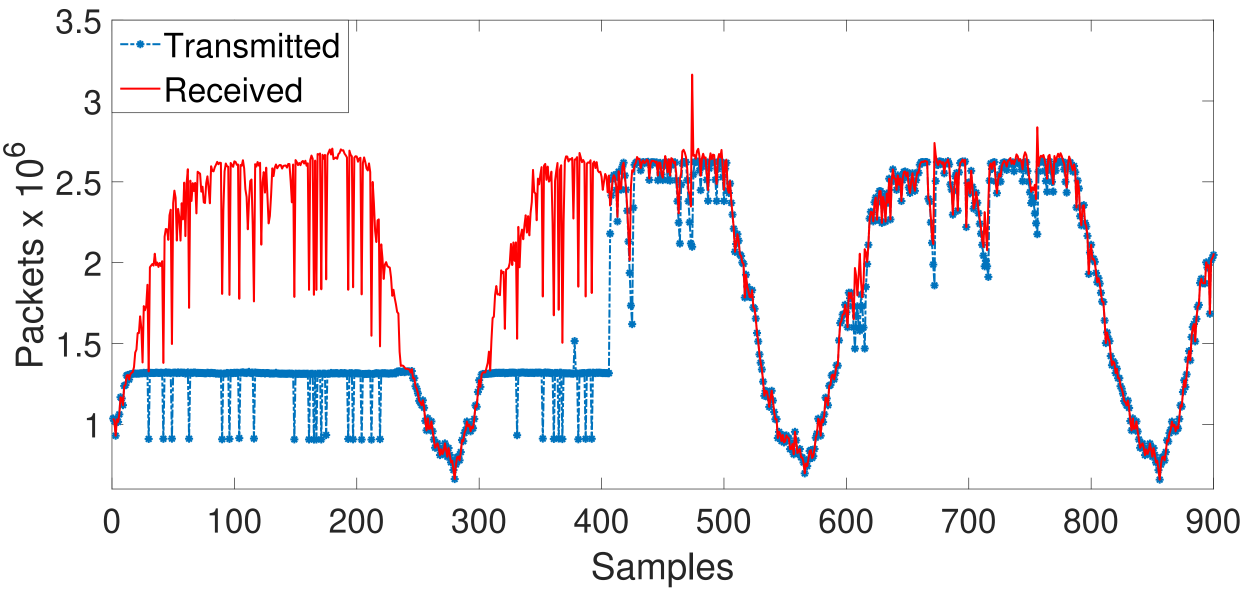


Figure 2.12: Static controller up to the $400th$, then MPC controller.

Chapter 3

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 2 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.).

3.1 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 choosen to take an intermediate step in which each device is associated with a dedicated hardware (unlike Mininet, where multiple virtual devices shared single hardware resorces). The used architecture is shown in Figure 3.1, where two Raspberry pi 3 [157] have been used has 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

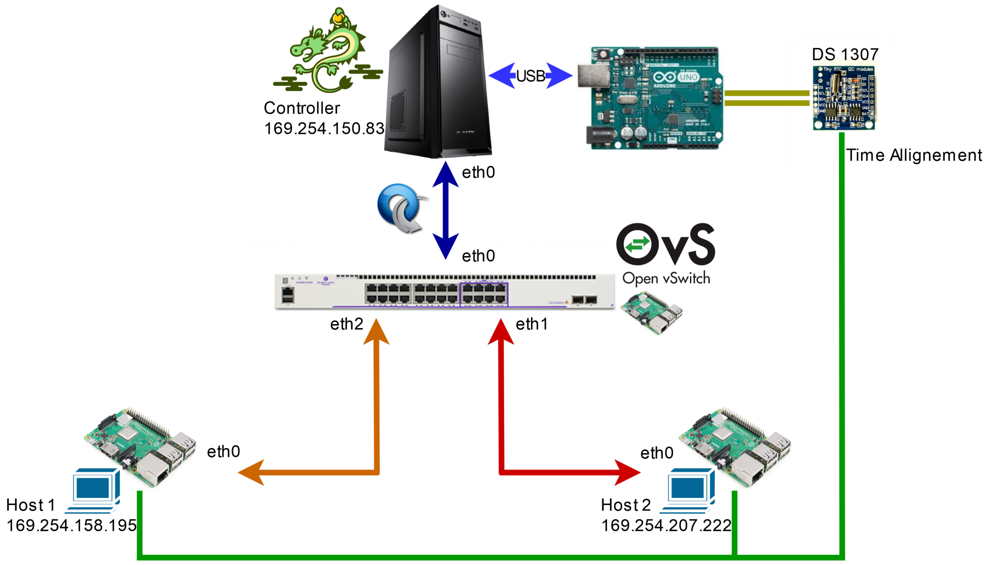


Figure 3.1: Network architecture with dedicated hardware devices.

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 2.1 (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 3.2(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 2.2 are applied with the same mathematical model used in Section 2.3.3. 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 3.2(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 3.2(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 2.3. 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.

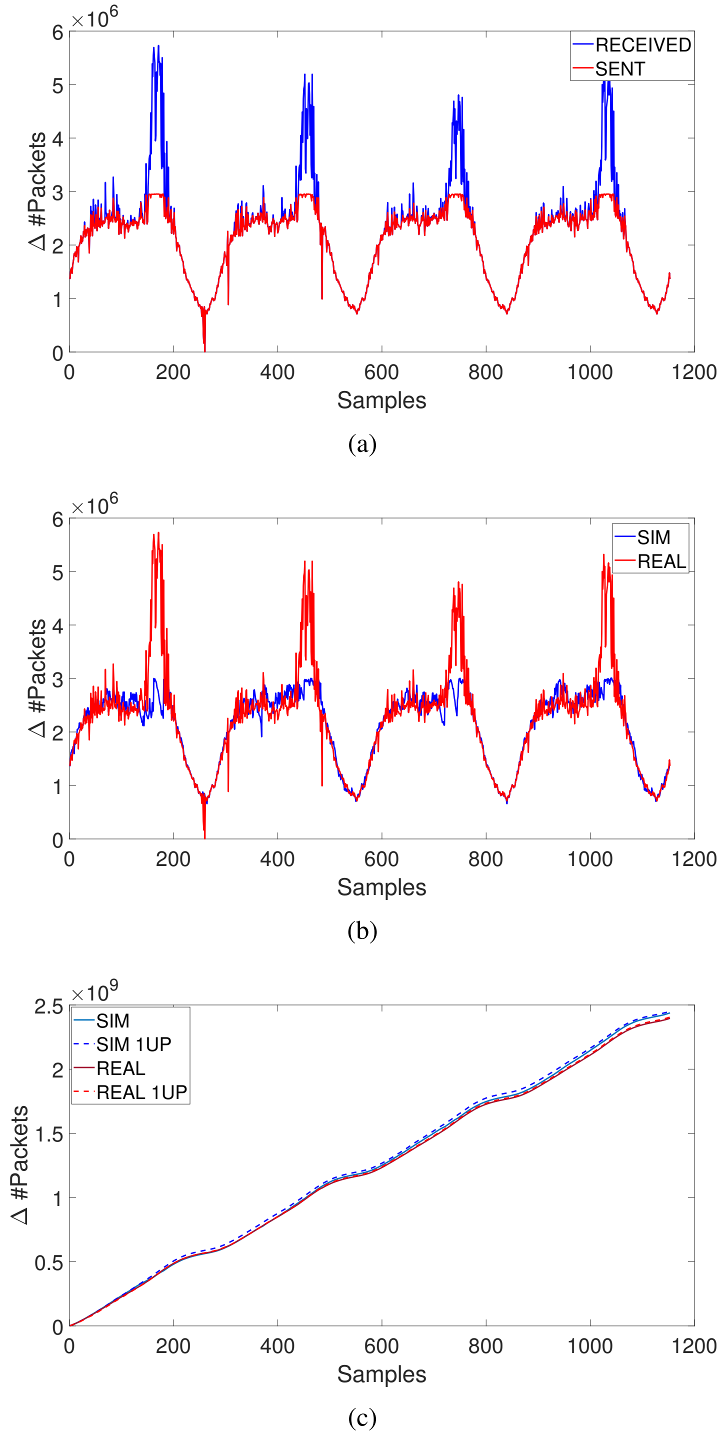


Figure 3.2: Packets that transit inside the switch (a), comparison between packets incoming in the switch in emulation environment and in dedicated hardware (b) and sum of packets sent by the switch port with different control model (c).

3.2 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].

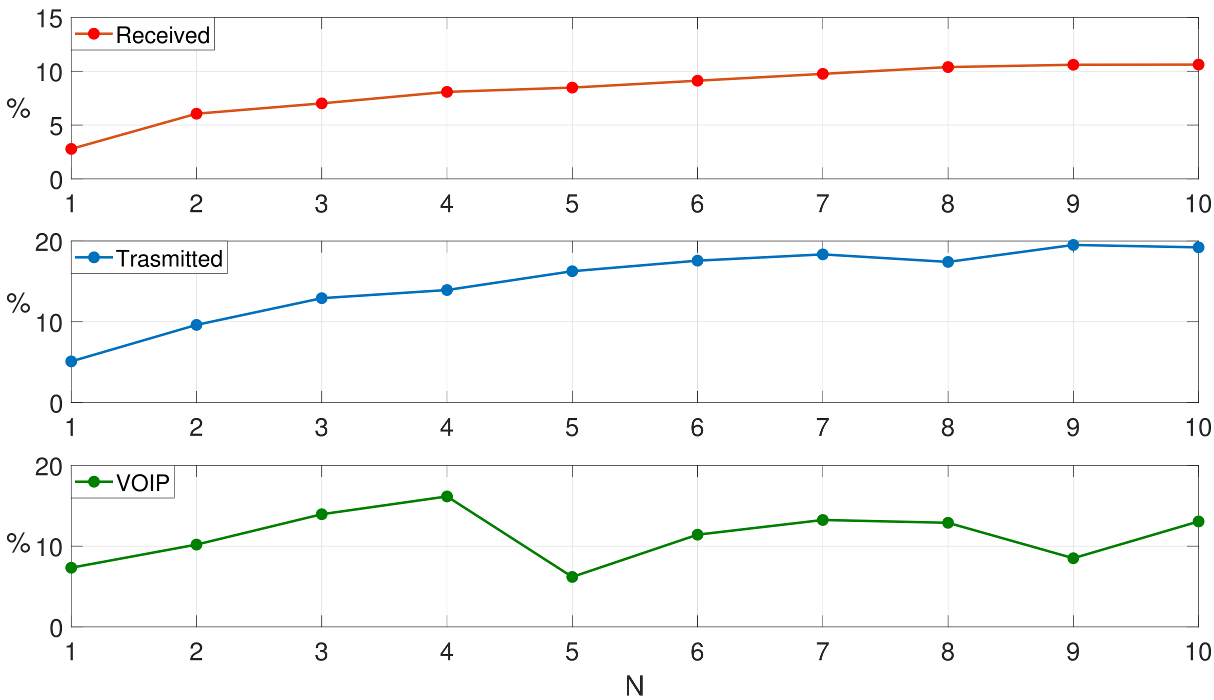


Figure 3.3: NRMSE of the packets predictive model over a time horizon of $N = 10$.

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 3.3 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 2.3. 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 3.4.

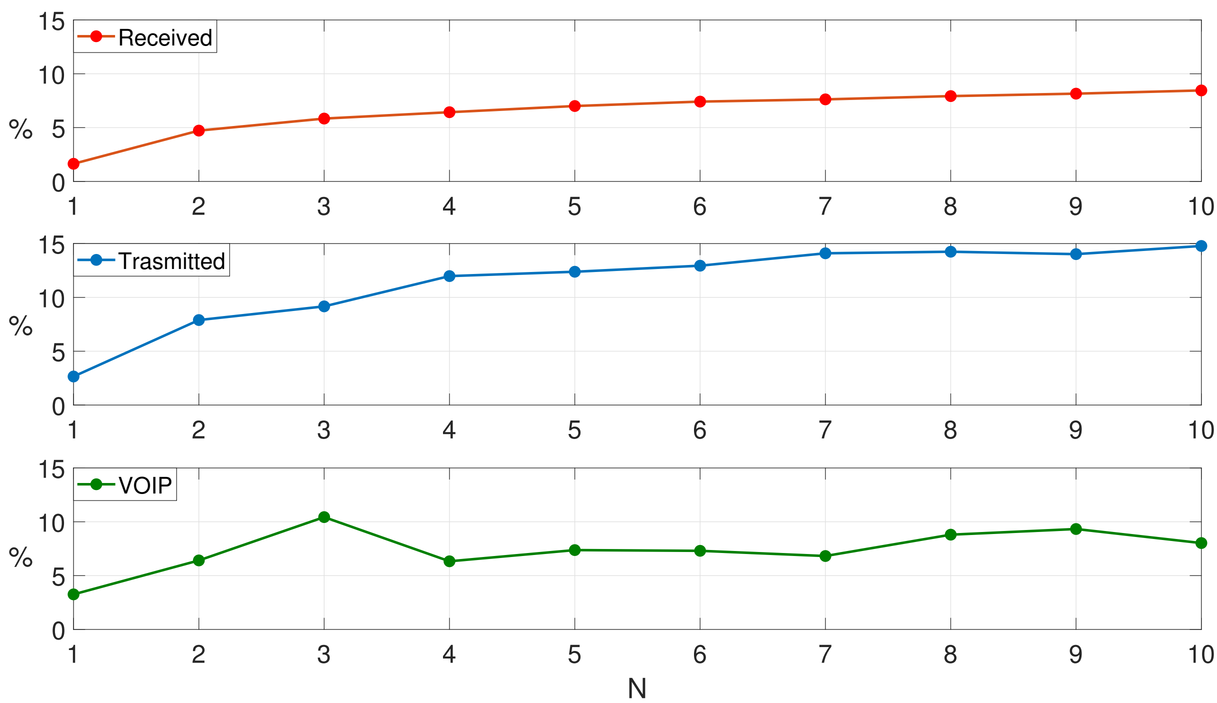


Figure 3.4: NRMSE of the packets predictive model over a time horizon of $N = 10$ after one data update.

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 3.4, 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 3.5 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 2 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.

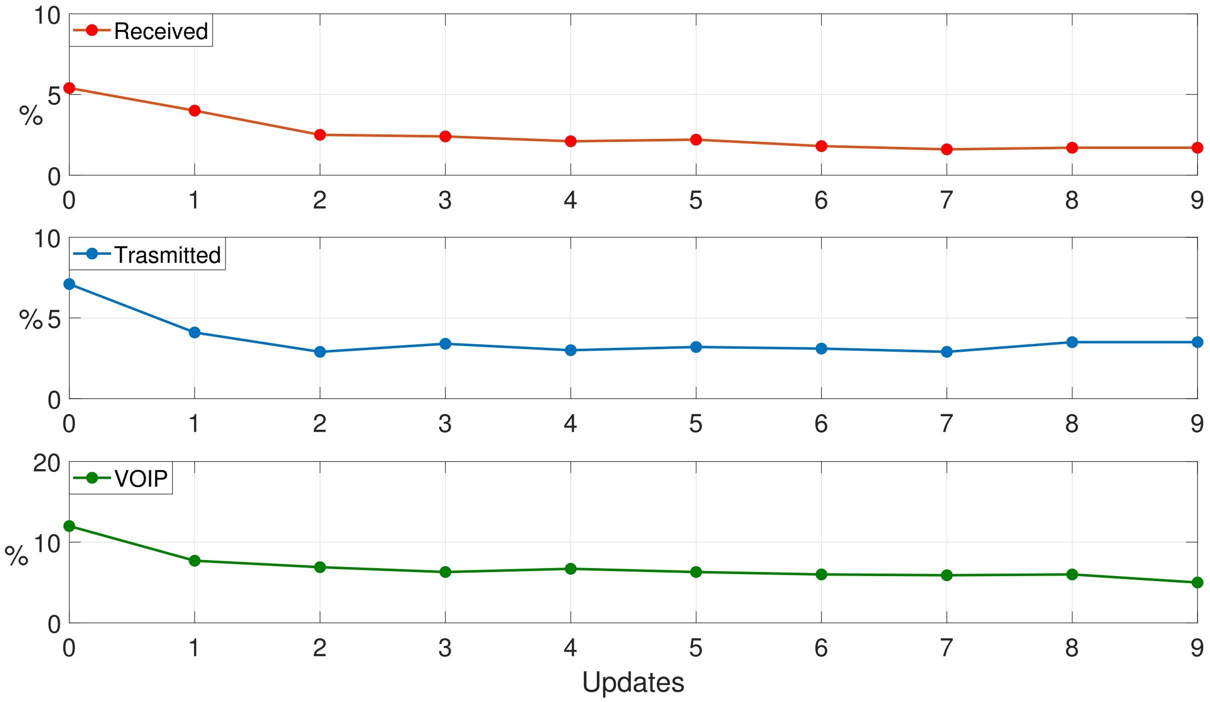


Figure 3.5: NRMSE of the packets predictive model at prediction horizon of N=1 with different updated models. Every update add 288 samples (about 1 day) to the previous model training data.

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

```
from ryu.base import app_manager
from ryu.controller import ofp_event
from ryu.controller.handler import CONFIG_DISPATCHER, MAIN_DISPATCHER
from ryu.controller.handler import set_ev_cls
from ryu.ofproto import ofproto_v1_3
from qos_simple_switch_13 import *
from datapath_monitor_TOS import *
from ryu.lib.packet import arp
from ryu.lib.packet.arp import ARP_REQUEST, ARP_REPLY
from ryu.lib.packet import ipv4


class MainControllerMonitor(app_manager.RyuApp):
    OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]

    def __init__(self, *args, **kwargs):
        super(MainControllerMonitor, self).__init__(*args, **kwargs)
        self.device_behaviour = SimpleSwitch13(*args, **kwargs)
        self.datapath_id_list = []
        self.mac_to_port = {}
        STEP = 300
        args = {
            "step":STEP,
            "logger":self.logger,
            "dp":self.datapath_id_list
        }
        self.monitor = DatapathMonitor(args)
        self.monitor.start()

    @set_ev_cls(ofp_event.EventOFPSwitchFeatures, CONFIG_DISPATCHER)
    def switch_feature_handler(self, ev):
        self.device_behaviour.switch_features_handler(ev)
        datapath = ev.msg.datapath
        if datapath not in self.datapath_id_list:
            self.datapath_id_list.append(datapath)
```

```
            self.monitor.update(self.datapath_id_list)

    @set_ev_cls(ofp_event.EventOFPPacketIn, MAIN_DISPATCHER)
    def _packet_in_handler(self, ev):
        self.device_behaviour._packet_in_handler(ev)

    @set_ev_cls(ofp_event.EventOFPDescStatsReply, MAIN_DISPATCHER)
    def desc_stat_reply_handler(self, ev):
        self.monitor.desc_reply(ev)
```

A.2 datapath_monitor_TOS.py

```
from ryu.controller import ofp_event
from ryu.controller.handler import CONFIG_DISPATCHER, MAIN_DISPATCHER
from ryu.ofproto import ofproto_v1_3
from ryu.lib.packet import packet
from ryu.lib.packet import ethernet
from ryu.lib.packet import ether_types
from operator import attrgetter
import threading
import time
import datetime

import subprocess
import json
import sys

from Controller_commands import *
import numpy as np

from subprocess import call
import random
import os

now=datetime.datetime.now()
year=str(now.year)
month=str(now.month)
day=str(now.day)
date=year+"-"+month+"-"+day+"_"
computername="jedi"
dpb_folder="/home/jedi/Dropbox/DataNetworkShared/"
file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/
    DataLog/"+date+"flowstat.txt","a")
stringa="time"+"\t"+"datapath"+"\t"+"in-port"+"\t"+"eth-dst"+"\t"+"out-
    port"+"\t"+"packets"+"\t"+"bytes"+"\t"+"ip_dscp"+"\t"+"SET_QUEUE\n"
file.write(stringa)
file.close()

file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/
    DataLog/"+date+"queuestat.txt","a")
```

```
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"
file.write(stringa)
file.close()

file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/DataLog/"+date+"portstat.txt","a")
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"
file.write(stringa)
file.close()

file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/DataLog/"+date+"queueconfig.txt","a")
stringa="time"+"\t"+"datapath"+"\t"+"queue_id"+"\t"+"type_of_rule"+"\t"+"rate\n"
file.write(stringa)
file.close()

f = open(dpb_folder+"FlagData.txt","w")
f.write("0")
f.close()

f = open(dpb_folder+"FlagU.txt","w")
f.write("0")
f.close()

def get_switchis():
    try:
        output = subprocess.check_output(
            "curl -X GET http://localhost:8080/stats/switches",
            stderr=subprocess.STDOUT,
            shell=True)
        output=output[output.find("["):]
        end_response=output.find("]")
        list1=list(output)
        list1[end_response]=','
        output=''.join(list1)+"]"
    except:
        output="No NET"
    return output

def save_flow_stat(datapath):
    datapath_in=datapath
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    try:
        output = subprocess.check_output(
            "curl -X GET http://localhost:8080/stats/flow/"+datapath,
            shell=True)
```

```
        i=0
        output = output[output.find("{")+1:]
        end_response = output.find("}]}")+2
        list1=list(output)
        list1[end_response-2]='}'
        list1[end_response-1]=','
        output=''.join(list1)
        while i<end_response:
            output_i=output[i:]
            i=i+output[i:].find("},")+2
            otp = output_i[output_i.find("{"):]
            otp = otp[0:otp.find("},")+1]
            otp =eval(otp)
            data = otp
            json_str = json.dumps(data)
            jsonList = json.loads(json_str)
            if jsonList['priority']!=0 and jsonList['match'].get('in_port'):
                porta=str(jsonList['actions'])
                prc = porta.find('T:')
                #Check if there is "OUTPUT:" in the string
                if prc >= 0:
                    porta=porta[prc+2:]
                    porta = int(porta[0:porta.find(']')-1])
                    file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/DataLog/"+date+"flowstat.txt","a")
                    now=datetime.datetime.now()
                    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"
                    file.write(stringa)
                    file.close()
                    file = open(dpb_folder+"DataFlow.txt","a")
                    file.write(stringa)
                    file.close()
                    file = open(dpb_folder+"DataFlowPrec.txt","a")
                    file.write(stringa)
                    file.close()
            if jsonList['priority']!=0 and str(jsonList['actions']).find('UE:')>=0:
                SET_QUEUE=str(str(jsonList['actions'])[str(jsonList['actions']).find('UE:')+3:str(jsonList['actions']).find(',')-1])
                file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/DataLog/"+date+"flowstat.txt","a")
                now=datetime.datetime.now()
                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"
                file.write(stringa)
                file.close()
                file = open(dpb_folder+"DataFlow.txt","a")
```

```
                file.write(stringa)
                file.close()
                file = open(dpb_folder+"DataFlowPrec.txt","a")
                file.write(stringa)
                file.close()

    except:
        print "FlowStat: No NET"

def save_port_stat(datapath):
    datapath_in=datapath
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    try:
        output = subprocess.check_output(
             "curl -X GET http://localhost:8080/stats/port/"+datapath,
             shell=True)
        i=0
        output = output[output.find("{")+1:]
        end_response = output.find("}]}")+2
        list1=list(output)
        list1[end_response-2]='}'
        list1[end_response-1]=','
        output=''.join(list1)
        while i<end_response:
            output_i=output[i:]
            i=i+output[i:].find("},")+2
            otp = output_i[output_i.find("{"):]
            otp = otp[0:otp.find("},")+1]
            otp =eval(otp)
            data = otp
            json_str = json.dumps(data)
            jsonList = json.loads(json_str)
            if jsonList['port_no']!="LOCAL":
                file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/DataLog/"+date+"portstat.txt","a")
                now=datetime.datetime.now()
                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"
                file.write(stringa)
                file.close()
                file = open(dpb_folder+"DataPort.txt","a")
                file.write(stringa)
                file.close()
                file = open(dpb_folder+"DataPortPrec.txt","a")
                file.write(stringa)
                file.close()

```

```
    except:
        print "PortStat: No NET"

def save_queue_stat(datapath):
    datapath_in=datapath
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    try:
        output = subprocess.check_output(
            "curl -X GET http://localhost:8080/qos/queue/status/"+
    datapath,
            shell=True)
        i=0
        output = output[output.find("ult")+1:]
        output = output[output.find("{")+1:]
        end_response = output.find("}]}")+2
        list1=list(output)
        list1[end_response-2]='}'
        list1[end_response-1]=','
        output=''.join(list1)
        if output[output.find(":")+2:output.find(":")+4]!="[]":
            while i<end_response:
                output_i=output[i:]
                i=i+output[i:].find("},")+2
                otp = output_i[output_i.find("{"):]
                otp = otp[0:otp.find("},")+1]
                otp = eval(otp)
                data = otp
                json_str = json.dumps(data)
                jsonList = json.loads(json_str)
                file = open("/home/"+computername+"/Scrivania/
    RyuDatapathMonitor-master/DataLog/"+date+"queuestat.txt","a")
                now=datetime.datetime.now()
                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"
                file.write(stringa)
                file.close()
                file = open(dpb_folder+"DataQueueStat.txt","a")
                file.write(stringa)
                file.close()
                file = open(dpb_folder+"DataQueueStatPrec.txt","a")
                file.write(stringa)
                file.close()

    except:
        print "QueueStat: No NET"

def save_queue_config(datapath):
    datapath_in=datapath
    mom_datapath= ['0' for i in range(16-len(datapath))]
```

```
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    try:
        output = subprocess.check_output(
            "curl -X GET http://localhost:8080/qos/queue/"+datapath,
            shell=True)
        i=0
        output=output[1:len(output)-1]
        jsonList = json.loads(output)
        config = jsonList['command_result'].get('details')
        for queue in config:
            if queue=='2':
                rate = jsonList['command_result'].get('details').get(queue).get('config').get('min-rate')
                type_of_rule='min_rate'
            else:
                rate = jsonList['command_result'].get('details').get(queue).get('config').get('max-rate')
                type_of_rule='max_rate'
            file = open("/home/"+computername+"/Scrivania/RyuDatapathMonitor-master/DataLog/"+date+"queueconfig.txt","a")
            now=datetime.datetime.now()
            stringa=str(now)+"\t"+datapath_in+"\t"+str(queue)+"\t"+str(type_of_rule)+"\t"+str(rate)+"\n"
            file.write(stringa)
            file.close()
            file = open(dpb_folder+"DataQueueConfig.txt","a")
            file.write(stringa)
            file.close()
            file = open(dpb_folder+"DataQueueConfigPrec.txt","a")
            file.write(stringa)
            file.close()

    except:
        print "QueueConfig: No NET"

class DatapathMonitor():
    OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]

    def __init__(self, args):
        self.datapath_list = args["dp"]

        self.monitor = threading.Thread(target=self.switch_monitor_thread)
        self.delta = args["step"]
        self.logger = args["logger"]

        self.started = False

    def start(self):
        self.monitor.start()
        self.started = True

    def update(self, dplist):
```

```
        self.datapath_list = dplist

    def switch_monitor_thread(self):
        max_rate_queue=100#Mps
        max_rate_queue=max_rate_queue*1000000
        minute_wait=20
        Time_queue=minute_wait*60
        Change_flag=Time_queue/self.delta
        counter=Change_flag
        c_q2=0
        c_q1=1
        c_q0=1
        q2=np.arange(70, 101, 10)*1000000
        q1=np.arange(0, 101, 10)*1000000
        q0=np.arange(0, 101, 10)*1000000

        print 'Wait for time alignment'
        wait=self.delta/60
        check_time=False
        while check_time==False:
            now=datetime.datetime.now()
            if now.minute%wait==0:
                check_time=True
            else:
                time.sleep(1)
        print 'Starting Save Data'
        check_time=False
        flag=0
        while True:
            while check_time==False:
                now=datetime.datetime.now()
                if now.minute%wait==0:
                    check_time=True
                    print "Save Time: "+str(now)
                else:
                    try:
                        time.sleep(1)
                        f = open(dpb_folder+"FlagU.txt","r")
                        flag=int(f.read())
                    except:
                        flag=0
                    try:
                        if flag==1:#check flag u file
                            time.sleep(10)
                            print("Change Queues Bw%")
                            f.close()
                            #Read new queue BW
                            i=0
                            u=[0,0,0]
                            with open(dpb_folder+"U.txt") as mytxt:
                                for line in mytxt:
                                    print (line)
                                    u[i]=int(line)*1000000
                                    i=i+1
```

```
                        #Set New Queue
                        set_queue("2", "s2-eth2", str(max_rate_queue), "{\"max_rate\": \""+str(u[0])+"\"}, {\"max_rate\": \""+str(u[1])+"\"}, {\"min_rate\": \""+str(u[2])+"\"}")
                        f = open(dpb_folder+"FlagU.txt","w")
                        f.write("0")
                        f.close()

                    else:
                        f.close()
                except:
                    print("BW File NOT READY")
        NET=get_switchis()
        t_sleep = 0.9
        if NET != "NO NET" and NET!="[,]":
            file = open(dpb_folder+"DataFlowPrec.txt","r")
            Prec=file.read()
            file.close()
            file = open(dpb_folder+"DataFlow.txt","w")
            file.write(Prec)
            file.close()
            file = open(dpb_folder+"DataFlowPrec.txt","w")
            file.close()

            file = open(dpb_folder+"DataPortPrec.txt","r")
            Prec=file.read()
            file.close()
            file = open(dpb_folder+"DataPort.txt","w")
            file.write(Prec)
            file.close()
            file = open(dpb_folder+"DataPortPrec.txt","w")
            file.close()

            file = open(dpb_folder+"DataQueueStatPrec.txt","r")
            Prec=file.read()
            file.close()
            file = open(dpb_folder+"DataQueueStat.txt","w")
            file.write(Prec)
            file.close()
            file = open(dpb_folder+"DataQueueStatPrec.txt","w")
            file.close()

            file = open(dpb_folder+"DataQueueConfigPrec.txt","r")
            Prec=file.read()
            file.close()
            file = open(dpb_folder+"DataQueueConfig.txt","w")
            file.write(Prec)
            file.close()
            file = open(dpb_folder+"DataQueueConfigPrec.txt","w")
            file.close()
            i=1
            while i<NET.find("]"):
                mom_NET=NET[i:]
                datapath=NET[i:i+mom_NET.find(",")]
```

```
                i=i+mom_NET.find(",")+2
                save_flow_stat(datapath)
                save_port_stat(datapath)
                save_queue_stat(datapath)
                save_queue_config(datapath)
            file = open(dpb_folder+"FlagData.txt","w")
            file.write("1")
            file.close()
            while check_time==True:
                now=datetime.datetime.now()
                if now.minute%wait!=0:
                    check_time=False
                else:
                    time.sleep(1)
                    try:
                        f = open(dpb_folder+"FlagU.txt","r")
                        flag=int(f.read())
                    except:
                        flag=0
                        continue
                    try:
                        if flag==1:#check flag u file
                            print("Change Queues Bw%")
                            f.close()
                            #Read new queue BW
                            i=0
                            u=[0,0,0]
                            with open(dpb_folder+"U.txt") as mytxt:
                                for line in mytxt:
                                    print (line)
                                    u[i]=int(line)*1000000
                                    i=i+1
                            #Set New Queue
                            set_queue("2", "s2-eth2", str(max_rate_queue), "{\"max_rate\": \""+str(u[0])+"\"}, {\"max_rate\": \""+str(u[1])+"\"}, {\"min_rate\": \""+str(u[2])+"\"}")
                            f = open(dpb_folder+"FlagU.txt","w")
                            f.write("0")
                            f.close()
                        else:
                            f.close()
                    except:
                        print("INPUT NOT READY")
                        continue
        else:
            print "No Network"
```

A.3 Controller_commands.py

```
from subprocess import call
import threading
```

```
import subprocess
import random
import os
import time
import json
import sys

def ovsdb_addr(datapath):
    datapath_in=datapath
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    print "Set ovsdb on switch "+datapath
    try:
        os.popen("sudo -S curl -X PUT -d '\"tcp:127.0.0.1:6632\"' http://localhost:8080/v1.0/conf/switches/"+datapath+"/ovsdb_addr", 'w').write("Ao70pa45")
        print "\n"
        time.sleep(2)
    except:
        print "ovsdb: ERROR"

def ovssctl_set_bridge(switch_name):
    print "Set ovssctl on switch "+switch_name
    try:
        os.popen("sudo -S ovs-vsctl set Bridge "+switch_name+" protocols=OpenFlow13", 'w').write("Ao70pa45")
        print "\n"
    except:
        print "ovssctl_set_bridge: ERROR"

def get_switchis():
    print "Get switches id"
    try:
        output = subprocess.check_output(
            "curl -X GET http://localhost:8080/stats/switches",
            stderr=subprocess.STDOUT,
            shell=True)
        output=output[output.find("["):]
        end_response=output.find("]")
        list1=list(output)
        list1[end_response]=','
        output=''.join(list1)+"]"
        print "\n"
    except:
        output="NO NET"
    return output

def switch_ports_name(datapath):
    datapath_in=datapath
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    print "Get names on switch "+datapath
```

```
    try:
        output = subprocess.check_output(
            "curl -X GET http://localhost:8080/stats/portdesc/"+
    datapath,
            stderr=subprocess.STDOUT,
            shell=True)
        i=0
        output = output[output.find("{")+1:]
        end_response = output.find("}]}")+2
        list1=list(output)
        list1[end_response-2]='}'
        list1[end_response-1]=','
        output=''.join(list1)
        names = []
        while i<end_response:
            output_i=output[i:]
            i=i+output[i:].find("},")+2
            otp = output_i[output_i.find("{"):]
            otp = otp[0:otp.find("},")+1]
            otp =eval(otp)
            data = otp
            json_str = json.dumps(data)
            jsonList = json.loads(json_str)
            if jsonList['port_no']=="LOCAL":
                names.append(str(jsonList['name']))
            else:
                names.append(str(jsonList['name']))
        print "\n"
        return names


    except:
        print "Switch port name: ERROR"


def queue_rule(datapath, port_number, ip_dscp, queue_number):
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    print "Set queue rule on switch "+datapath+" on port "+port_number
    try:
        os.popen("curl -X POST -d '{\"match\": {\"ip_dscp\": \""+ip_dscp
    +"\"}, \"actions\":{\"queue\": \""+queue_number+"\"}}' http://
    localhost:8080/qos/rules/"+datapath, 'w').write("Ao70pa45")
        time.sleep(0.1)
        print "\n"
    except:
        print "Set queue rule: Error"

def queue_rule_byIP(datapath, port_number, ip_dscp, queue_number, ip_dst
    ):
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
```

```
    print "Set queue rule on switch "+datapath+" on port "+port_number
    try:
        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")
        time.sleep(0.1)
        print "\n"
    except:
        print "Set queue rule: Error"

def set_queue(datapath, port_id, max_rate, queue_rate_list):
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    print "Set queue on port "+port_id+" of switch "+datapath
    print queue_rate_list
    try:
        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,
                stderr=subprocess.STDOUT,
                shell=True)
        time.sleep(0.1)
        print "\n"
    except:
        print "Set queue: Error"


def set_Telecom_queue(datapath, port_number, IP_flag, IP_dst):
    port=port_number
    mom_datapath= ['0' for i in range(16-len(datapath))]
    mom_datapath=''.join(mom_datapath)
    datapath=mom_datapath+datapath
    if IP_flag==True:
        queue_rule_byIP(datapath, port, "0", "0", IP_dst)#Service 0
        queue_rule_byIP(datapath, port, "8", "0", IP_dst)#Service 1
        queue_rule_byIP(datapath, port, "10", "0", IP_dst)#Service 1
        queue_rule_byIP(datapath, port, "12", "0", IP_dst)#Service 1
        queue_rule_byIP(datapath, port, "14", "0", IP_dst)#Service 1
        queue_rule_byIP(datapath, port, "24", "0", IP_dst)#Service 3
        queue_rule_byIP(datapath, port, "26", "0", IP_dst)#Service 3
        queue_rule_byIP(datapath, port, "28", "0", IP_dst)#Service 3
        queue_rule_byIP(datapath, port, "30", "0", IP_dst)#Service 3

        queue_rule_byIP(datapath, port, "16", "1", IP_dst)#Service 2
        queue_rule_byIP(datapath, port, "18", "1", IP_dst)#Service 2
        queue_rule_byIP(datapath, port, "20", "1", IP_dst)#Service 2
        queue_rule_byIP(datapath, port, "22", "1", IP_dst)#Service 2
        queue_rule_byIP(datapath, port, "32", "1", IP_dst)#Service 4
        queue_rule_byIP(datapath, port, "34", "1", IP_dst)#Service 4
        queue_rule_byIP(datapath, port, "36", "1", IP_dst)#Service 4
        queue_rule_byIP(datapath, port, "38", "1", IP_dst)#Service 4
```

```
        queue_rule_byIP(datapath, port, "48", "1", IP_dst)#Service 6
        queue_rule_byIP(datapath, port, "56", "1", IP_dst)#Service 7

        queue_rule_byIP(datapath, port, "40", "2", IP_dst)#Service 5
        queue_rule_byIP(datapath, port, "46", "2", IP_dst)#Service 5

    if IP_flag==False:
        #Default Queue (queue_id = 0)
        queue_rule(datapath, port, "0", "0")#Service 0
        queue_rule(datapath, port, "8", "0")#Service 1
        queue_rule(datapath, port, "10", "0")#Service 1
        queue_rule(datapath, port, "12", "0")#Service 1
        queue_rule(datapath, port, "14", "0")#Service 1
        queue_rule(datapath, port, "24", "0")#Service 3
        queue_rule(datapath, port, "26", "0")#Service 3
        queue_rule(datapath, port, "28", "0")#Service 3
        queue_rule(datapath, port, "30", "0")#Service 3
        #Premium Queue (queue_id = 1)
        queue_rule(datapath, port, "16", "1")#Service 2
        queue_rule(datapath, port, "18", "1")#Service 2
        queue_rule(datapath, port, "20", "1")#Service 2
        queue_rule(datapath, port, "22", "1")#Service 2
        queue_rule(datapath, port, "32", "1")#Service 4
        queue_rule(datapath, port, "34", "1")#Service 4
        queue_rule(datapath, port, "36", "1")#Service 4
        queue_rule(datapath, port, "38", "1")#Service 4
        queue_rule(datapath, port, "48", "1")#Service 6
        queue_rule(datapath, port, "56", "1")#Service 7
        #Gold Queue (queue_id = 2)
        queue_rule(datapath, port, "40", "2")#Service 5
        queue_rule(datapath, port, "46", "2")#Service 5
```

A.4 qos_simple_switch_13.py

```
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# WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or
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# limitations under the License.

from ryu.base import app_manager
from ryu.controller import ofp_event
```

```python
from ryu.controller.handler import CONFIG_DISPATCHER, MAIN_DISPATCHER
from ryu.controller.handler import set_ev_cls
from ryu.ofproto import ofproto_v1_3
from ryu.lib.packet import packet
from ryu.lib.packet import ethernet
from ryu.lib.packet import ether_types

import subprocess


class SimpleSwitch13(app_manager.RyuApp):
    OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]

    def __init__(self, *args, **kwargs):
        super(SimpleSwitch13, self).__init__(*args, **kwargs)
        self.mac_to_port = {}

    @set_ev_cls(ofp_event.EventOFPSwitchFeatures, CONFIG_DISPATCHER)
    def switch_features_handler(self, ev):
        datapath = ev.msg.datapath
        ofproto = datapath.ofproto
        parser = datapath.ofproto_parser

        # install table-miss flow entry
        #
        # We specify NO BUFFER to max_len of the output action due to
        # OVS bug. At this moment, if we specify a lesser number, e.g.,
        # 128, OVS will send Packet-In with invalid buffer_id and
        # truncated packet data. In that case, we cannot output packets
        # correctly.  The bug has been fixed in OVS v2.1.0.
        match = parser.OFPMatch()
        actions = [parser.OFPActionOutput(ofproto.OFPP_CONTROLLER,
                                          ofproto.OFPCML_NO_BUFFER)]
        self.add_flow(datapath, 0, match, actions)

    def add_flow(self, datapath, priority, match, actions, buffer_id=None):
        ofproto = datapath.ofproto
        parser = datapath.ofproto_parser

        inst = [parser.OFPInstructionActions(ofproto.OFPIT_APPLY_ACTIONS,
                                             actions)]
        if buffer_id:
            mod = parser.OFPFlowMod(datapath=datapath, buffer_id=buffer_id,
                                    priority=priority, match=match,
                                    instructions=inst, table_id=1)
        else:
            mod = parser.OFPFlowMod(datapath=datapath, priority=priority,
                                    match=match, instructions=inst, table_id=1)
        datapath.send_msg(mod)
```

```python

    @set_ev_cls(ofp_event.EventOFPPacketIn, MAIN_DISPATCHER)
    def _packet_in_handler(self, ev):
        # If you hit this you might want to increase
        # the "miss_send_length" of your switch
        if ev.msg.msg_len < ev.msg.total_len:
            self.logger.debug("packet truncated: only %s of %s bytes",
                              ev.msg.msg_len, ev.msg.total_len)
        msg = ev.msg
        datapath = msg.datapath
        ofproto = datapath.ofproto
        parser = datapath.ofproto_parser
        in_port = msg.match['in_port']

        pkt = packet.Packet(msg.data)
        eth = pkt.get_protocols(ethernet.ethernet)[0]

        if eth.ethertype == ether_types.ETH_TYPE_LLDP:
            # ignore lldp packet
            return
        dst = eth.dst
        src = eth.src

        dpid = datapath.id
        self.mac_to_port.setdefault(dpid, {})

        # learn a mac address to avoid FLOOD next time.
        self.mac_to_port[dpid][src] = in_port

        if dst in self.mac_to_port[dpid]:
            out_port = self.mac_to_port[dpid][dst]
        else:
            out_port = ofproto.OFPP_FLOOD

        actions = [parser.OFPActionOutput(out_port)]

        # install a flow to avoid packet_in next time
        if out_port != ofproto.OFPP_FLOOD:
            match = parser.OFPMatch(in_port=in_port, eth_dst=dst, eth_src=src)
            # verify if we have a valid buffer_id, if yes avoid to send both
            # flow_mod & packet_out
            if msg.buffer_id != ofproto.OFP_NO_BUFFER:
                self.add_flow(datapath, 1, match, actions, msg.buffer_id)
                return
            else:
                self.add_flow(datapath, 1, match, actions)
        data = None
        if msg.buffer_id == ofproto.OFP_NO_BUFFER:
            data = msg.data

```

```
        out = parser.OFPPacketOut(datapath=datapath, buffer_id=msg.buffer_id,
                                  in_port=in_port, actions=actions, data=data)
        datapath.send_msg(out)
```

A.5 ofctl_rest.py

```
# Copyright (C) 2012 Nippon Telegraph and Telephone Corporation.
#
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# distributed under the License is distributed on an "AS IS" BASIS,
# WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or
# implied.
# See the License for the specific language governing permissions and
# limitations under the License.

import logging
import json
import ast

from ryu.base import app_manager
from ryu.controller import ofp_event
from ryu.controller import dpset
from ryu.controller.handler import MAIN_DISPATCHER
from ryu.controller.handler import set_ev_cls
from ryu.exception import RyuException
from ryu.ofproto import ofproto_v1_0
from ryu.ofproto import ofproto_v1_2
from ryu.ofproto import ofproto_v1_3
from ryu.ofproto import ofproto_v1_4
from ryu.ofproto import ofproto_v1_5
from ryu.lib import ofctl_v1_0
from ryu.lib import ofctl_v1_2
from ryu.lib import ofctl_v1_3
from ryu.lib import ofctl_v1_4
from ryu.lib import ofctl_v1_5
from ryu.app.wsgi import ControllerBase
from ryu.app.wsgi import Response
from ryu.app.wsgi import WSGIApplication

LOG = logging.getLogger('ryu.app.ofctl_rest')

# supported ofctl versions in this restful app
supported_ofctl = {
```

```
    ofproto_v1_0.OFP_VERSION: ofctl_v1_0,
    ofproto_v1_2.OFP_VERSION: ofctl_v1_2,
    ofproto_v1_3.OFP_VERSION: ofctl_v1_3,
    ofproto_v1_4.OFP_VERSION: ofctl_v1_4,
    ofproto_v1_5.OFP_VERSION: ofctl_v1_5,
}

# REST API
#

# Retrieve the switch stats
#
# get the list of all switches
# GET /stats/switches
#
# get the desc stats of the switch
# GET /stats/desc/<dpid>
#
# get flows desc stats of the switch
# GET /stats/flowdesc/<dpid>
#
# get flows desc stats of the switch filtered by the fields
# POST /stats/flowdesc/<dpid>
#
# get flows stats of the switch
# GET /stats/flow/<dpid>
#
# get flows stats of the switch filtered by the fields
# POST /stats/flow/<dpid>
#
# get aggregate flows stats of the switch
# GET /stats/aggregateflow/<dpid>
#
# get aggregate flows stats of the switch filtered by the fields
# POST /stats/aggregateflow/<dpid>
#
# get table stats of the switch
# GET /stats/table/<dpid>
#
# get table features stats of the switch
# GET /stats/tablefeatures/<dpid>
#
# get ports stats of the switch
# GET /stats/port/<dpid>[/<port>]
# Note: Specification of port number is optional
#
# get queues stats of the switch
# GET /stats/queue/<dpid>[/<port>[/<queue_id>]]
# Note: Specification of port number and queue id are optional
#       If you want to omitting the port number and setting the queue id,
#       please specify the keyword "ALL" to the port number
#       e.g. GET /stats/queue/1/ALL/1
#
```

```
# get queues config stats of the switch
# GET /stats/queueconfig/<dpid>[/<port>]
# Note: Specification of port number is optional
#
# get queues desc stats of the switch
# GET /stats/queuedesc/<dpid>[/<port>[/<queue_id>]]
# Note: Specification of port number and queue id are optional
#       If you want to omitting the port number and setting the queue id
    ,
#       please specify the keyword "ALL" to the port number
#       e.g. GET /stats/queuedesc/1/ALL/1
#
# get meter features stats of the switch
# GET /stats/meterfeatures/<dpid>
#
# get meter config stats of the switch
# GET /stats/meterconfig/<dpid>[/<meter_id>]
# Note: Specification of meter id is optional
#
# get meter desc stats of the switch
# GET /stats/meterdesc/<dpid>[/<meter_id>]
# Note: Specification of meter id is optional
#
# get meters stats of the switch
# GET /stats/meter/<dpid>[/<meter_id>]
# Note: Specification of meter id is optional
#
# get group features stats of the switch
# GET /stats/groupfeatures/<dpid>
#
# get groups desc stats of the switch
# GET /stats/groupdesc/<dpid>[/<group_id>]
# Note: Specification of group id is optional (OpenFlow 1.5 or later)
#
# get groups stats of the switch
# GET /stats/group/<dpid>[/<group_id>]
# Note: Specification of group id is optional
#
# get ports description of the switch
# GET /stats/portdesc/<dpid>[/<port_no>]
# Note: Specification of port number is optional (OpenFlow 1.5 or later)

# Update the switch stats
#
# add a flow entry
# POST /stats/flowentry/add
#
# modify all matching flow entries
# POST /stats/flowentry/modify
#
# modify flow entry strictly matching wildcards and priority
# POST /stats/flowentry/modify_strict
#
# delete all matching flow entries
```

```
# POST /stats/flowentry/delete
#
# delete flow entry strictly matching wildcards and priority
# POST /stats/flowentry/delete_strict
#
# delete all flow entries of the switch
# DELETE /stats/flowentry/clear/<dpid>
#
# add a meter entry
# POST /stats/meterentry/add
#
# modify a meter entry
# POST /stats/meterentry/modify
#
# delete a meter entry
# POST /stats/meterentry/delete
#
# add a group entry
# POST /stats/groupentry/add
#
# modify a group entry
# POST /stats/groupentry/modify
#
# delete a group entry
# POST /stats/groupentry/delete
#
# modify behavior of the physical port
# POST /stats/portdesc/modify
#
# modify role of controller
# POST /stats/role
#
#
# send a experimeter message
# POST /stats/experimenter/<dpid>


class CommandNotFoundError(RyuException):
    message = 'No such command : %(cmd)s'


class PortNotFoundError(RyuException):
    message = 'No such port info: %(port_no)s'


def stats_method(method):
    def wrapper(self, req, dpid, *args, **kwargs):
        # Get datapath instance from DPSet
        try:
            dp = self.dpset.get(int(str(dpid), 0))
        except ValueError:
            LOG.exception('Invalid dpid: %s', dpid)
            return Response(status=400)
        if dp is None:
```

```
            LOG.error('No such Datapath: %s', dpid)
            return Response(status=404)

        # Get lib/ofctl_* module
        try:
            ofctl = supported_ofctl.get(dp.ofproto.OFP_VERSION)
        except KeyError:
            LOG.exception('Unsupported OF version: %s',
                          dp.ofproto.OFP_VERSION)
            return Response(status=501)

        # Invoke StatsController method
        try:
            ret = method(self, req, dp, ofctl, *args, **kwargs)
            return Response(content_type='application/json',
                            body=json.dumps(ret))
        except ValueError:
            LOG.exception('Invalid syntax: %s', req.body)
            return Response(status=400)
        except AttributeError:
            LOG.exception('Unsupported OF request in this version: %s',
                          dp.ofproto.OFP_VERSION)
            return Response(status=501)

    return wrapper


def command_method(method):
    def wrapper(self, req, *args, **kwargs):
        # Parse request json body
        try:
            if req.body:
                # We use ast.literal_eval() to parse request json body
                # instead of json.loads().
                # Because we need to parse binary format body
                # in send_experimenter().
                body = ast.literal_eval(req.body.decode('utf-8'))
            else:
                body = {}
        except SyntaxError:
            LOG.exception('Invalid syntax: %s', req.body)
            return Response(status=400)

        # Get datapath_id from request parameters
        dpid = body.get('dpid', None)
        if not dpid:
            try:
                dpid = kwargs.pop('dpid')
            except KeyError:
                LOG.exception('Cannot get dpid from request parameters')
                return Response(status=400)

        # Get datapath instance from DPSet
        try:
```

```
            dp = self.dpset.get(int(str(dpid), 0))
        except ValueError:
            LOG.exception('Invalid dpid: %s', dpid)
            return Response(status=400)
        if dp is None:
            LOG.error('No such Datapath: %s', dpid)
            return Response(status=404)

        # Get lib/ofctl_* module
        try:
            ofctl = supported_ofctl.get(dp.ofproto.OFP_VERSION)
        except KeyError:
            LOG.exception('Unsupported OF version: version=%s',
                          dp.ofproto.OFP_VERSION)
            return Response(status=501)

        # Invoke StatsController method
        try:
            method(self, req, dp, ofctl, body, *args, **kwargs)
            return Response(status=200)
        except ValueError:
            LOG.exception('Invalid syntax: %s', req.body)
            return Response(status=400)
        except AttributeError:
            LOG.exception('Unsupported OF request in this version: %s',
                          dp.ofproto.OFP_VERSION)
            return Response(status=501)
        except CommandNotFoundError as e:
            LOG.exception(e.message)
            return Response(status=404)
        except PortNotFoundError as e:
            LOG.exception(e.message)
            return Response(status=404)

    return wrapper


class StatsController(ControllerBase):
    def __init__(self, req, link, data, **config):
        super(StatsController, self).__init__(req, link, data, **config)
        self.dpset = data['dpset']
        self.waiters = data['waiters']

    def get_dpids(self, req, **_kwargs):
        dps = list(self.dpset.dps.keys())
        body = json.dumps(dps)
        return Response(content_type='application/json', body=body)

    @stats_method
    def get_desc_stats(self, req, dp, ofctl, **kwargs):
        return ofctl.get_desc_stats(dp, self.waiters)

    @stats_method
    def get_flow_desc(self, req, dp, ofctl, **kwargs):
```

```
        flow = req.json if req.body else {}
        return ofctl.get_flow_desc(dp, self.waiters, flow)

    @stats_method
    def get_flow_stats(self, req, dp, ofctl, **kwargs):
        flow = req.json if req.body else {}
        return ofctl.get_flow_stats(dp, self.waiters, flow)

    @stats_method
    def get_aggregate_flow_stats(self, req, dp, ofctl, **kwargs):
        flow = req.json if req.body else {}
        return ofctl.get_aggregate_flow_stats(dp, self.waiters, flow)

    @stats_method
    def get_table_stats(self, req, dp, ofctl, **kwargs):
        return ofctl.get_table_stats(dp, self.waiters)

    @stats_method
    def get_table_features(self, req, dp, ofctl, **kwargs):
        return ofctl.get_table_features(dp, self.waiters)

    @stats_method
    def get_port_stats(self, req, dp, ofctl, port=None, **kwargs):
        if port == "ALL":
            port = None

        return ofctl.get_port_stats(dp, self.waiters, port)

    @stats_method
    def get_queue_stats(self, req, dp, ofctl,
                        port=None, queue_id=None, **kwargs):
        if port == "ALL":
            port = None

        if queue_id == "ALL":
            queue_id = None

        return ofctl.get_queue_stats(dp, self.waiters, port, queue_id)

    @stats_method
    def get_queue_config(self, req, dp, ofctl, port=None, **kwargs):
        if port == "ALL":
            port = None

        return ofctl.get_queue_config(dp, self.waiters, port)

    @stats_method
    def get_queue_desc(self, req, dp, ofctl,
                       port=None, queue=None, **_kwargs):
        if port == "ALL":
            port = None

        if queue == "ALL":
            queue = None
```

```python

        return ofctl.get_queue_desc(dp, self.waiters, port, queue)

    @stats_method
    def get_meter_features(self, req, dp, ofctl, **kwargs):
        return ofctl.get_meter_features(dp, self.waiters)

    @stats_method
    def get_meter_config(self, req, dp, ofctl, meter_id=None, **kwargs):
        if meter_id == "ALL":
            meter_id = None

        return ofctl.get_meter_config(dp, self.waiters, meter_id)

    @stats_method
    def get_meter_desc(self, req, dp, ofctl, meter_id=None, **kwargs):
        if meter_id == "ALL":
            meter_id = None

        return ofctl.get_meter_desc(dp, self.waiters, meter_id)

    @stats_method
    def get_meter_stats(self, req, dp, ofctl, meter_id=None, **kwargs):
        if meter_id == "ALL":
            meter_id = None

        return ofctl.get_meter_stats(dp, self.waiters, meter_id)

    @stats_method
    def get_group_features(self, req, dp, ofctl, **kwargs):
        return ofctl.get_group_features(dp, self.waiters)

    @stats_method
    def get_group_desc(self, req, dp, ofctl, group_id=None, **kwargs):
        if dp.ofproto.OFP_VERSION < ofproto_v1_5.OFP_VERSION:
            return ofctl.get_group_desc(dp, self.waiters)
        else:
            return ofctl.get_group_desc(dp, self.waiters, group_id)

    @stats_method
    def get_group_stats(self, req, dp, ofctl, group_id=None, **kwargs):
        if group_id == "ALL":
            group_id = None

        return ofctl.get_group_stats(dp, self.waiters, group_id)

    @stats_method
    def get_port_desc(self, req, dp, ofctl, port_no=None, **kwargs):
        if dp.ofproto.OFP_VERSION < ofproto_v1_5.OFP_VERSION:
            return ofctl.get_port_desc(dp, self.waiters)
        else:
            return ofctl.get_port_desc(dp, self.waiters, port_no)

    @stats_method
```

```
    def get_role(self, req, dp, ofctl, **kwargs):
        return ofctl.get_role(dp, self.waiters)

    @command_method
    def mod_flow_entry(self, req, dp, ofctl, flow, cmd, **kwargs):
        cmd_convert = {
            'add': dp.ofproto.OFPFC_ADD,
            'modify': dp.ofproto.OFPFC_MODIFY,
            'modify_strict': dp.ofproto.OFPFC_MODIFY_STRICT,
            'delete': dp.ofproto.OFPFC_DELETE,
            'delete_strict': dp.ofproto.OFPFC_DELETE_STRICT,
        }
        mod_cmd = cmd_convert.get(cmd, None)
        if mod_cmd is None:
            raise CommandNotFoundError(cmd=cmd)

        ofctl.mod_flow_entry(dp, flow, mod_cmd)

    @command_method
    def delete_flow_entry(self, req, dp, ofctl, flow, **kwargs):
        if ofproto_v1_0.OFP_VERSION == dp.ofproto.OFP_VERSION:
            flow = {}
        else:
            flow = {'table_id': dp.ofproto.OFPTT_ALL}

        ofctl.mod_flow_entry(dp, flow, dp.ofproto.OFPFC_DELETE)

    @command_method
    def mod_meter_entry(self, req, dp, ofctl, meter, cmd, **kwargs):
        cmd_convert = {
            'add': dp.ofproto.OFPMC_ADD,
            'modify': dp.ofproto.OFPMC_MODIFY,
            'delete': dp.ofproto.OFPMC_DELETE,
        }
        mod_cmd = cmd_convert.get(cmd, None)
        if mod_cmd is None:
            raise CommandNotFoundError(cmd=cmd)

        ofctl.mod_meter_entry(dp, meter, mod_cmd)

    @command_method
    def mod_group_entry(self, req, dp, ofctl, group, cmd, **kwargs):
        cmd_convert = {
            'add': dp.ofproto.OFPGC_ADD,
            'modify': dp.ofproto.OFPGC_MODIFY,
            'delete': dp.ofproto.OFPGC_DELETE,
        }
        mod_cmd = cmd_convert.get(cmd, None)
        if mod_cmd is None:
            raise CommandNotFoundError(cmd=cmd)

        ofctl.mod_group_entry(dp, group, mod_cmd)

    @command_method
```

```
    def mod_port_behavior(self, req, dp, ofctl, port_config, cmd, **kwargs):
        port_no = port_config.get('port_no', None)
        port_no = int(str(port_no), 0)

        port_info = self.dpset.port_state[int(dp.id)].get(port_no)
        if port_info:
            port_config.setdefault('hw_addr', port_info.hw_addr)
            if dp.ofproto.OFP_VERSION < ofproto_v1_4.OFP_VERSION:
                port_config.setdefault('advertise', port_info.advertised)
            else:
                port_config.setdefault('properties', port_info.properties)
        else:
            raise PortNotFoundError(port_no=port_no)

        if cmd != 'modify':
            raise CommandNotFoundError(cmd=cmd)

        ofctl.mod_port_behavior(dp, port_config)

    @command_method
    def send_experimenter(self, req, dp, ofctl, exp, **kwargs):
        ofctl.send_experimenter(dp, exp)

    @command_method
    def set_role(self, req, dp, ofctl, role, **kwargs):
        ofctl.set_role(dp, role)


class RestStatsApi(app_manager.RyuApp):
    OFP_VERSIONS = [ofproto_v1_0.OFP_VERSION,
                    ofproto_v1_2.OFP_VERSION,
                    ofproto_v1_3.OFP_VERSION,
                    ofproto_v1_4.OFP_VERSION,
                    ofproto_v1_5.OFP_VERSION]
    _CONTEXTS = {
        'dpset': dpset.DPSet,
        'wsgi': WSGIApplication
    }

    def __init__(self, *args, **kwargs):
        super(RestStatsApi, self).__init__(*args, **kwargs)
        self.dpset = kwargs['dpset']
        wsgi = kwargs['wsgi']
        self.waiters = {}
        self.data = {}
        self.data['dpset'] = self.dpset
        self.data['waiters'] = self.waiters
        mapper = wsgi.mapper

        wsgi.registory['StatsController'] = self.data
        path = '/stats'
```

```
        uri = path + '/switches'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_dpids',
                       conditions=dict(method=['GET']))

        uri = path + '/desc/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_desc_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/flowdesc/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_flow_stats',
                       conditions=dict(method=['GET', 'POST']))

        uri = path + '/flow/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_flow_stats',
                       conditions=dict(method=['GET', 'POST']))

        uri = path + '/aggregateflow/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController,
                       action='get_aggregate_flow_stats',
                       conditions=dict(method=['GET', 'POST']))

        uri = path + '/table/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_table_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/tablefeatures/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_table_features',
                       conditions=dict(method=['GET']))

        uri = path + '/port/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_port_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/port/{dpid}/{port}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_port_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/queue/{dpid}'
```

```
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/queue/{dpid}/{port}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/queue/{dpid}/{port}/{queue_id}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/queueconfig/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_config',
                       conditions=dict(method=['GET']))

        uri = path + '/queueconfig/{dpid}/{port}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_config',
                       conditions=dict(method=['GET']))

        uri = path + '/queuedesc/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_desc',
                       conditions=dict(method=['GET']))

        uri = path + '/queuedesc/{dpid}/{port}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_desc',
                       conditions=dict(method=['GET']))

        uri = path + '/queuedesc/{dpid}/{port}/{queue}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_queue_desc',
                       conditions=dict(method=['GET']))

        uri = path + '/meterfeatures/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_meter_features',
                       conditions=dict(method=['GET']))

        uri = path + '/meterconfig/{dpid}'
```

```
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_meter_config',
                       conditions=dict(method=['GET']))

        uri = path + '/meterconfig/{dpid}/{meter_id}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_meter_config',
                       conditions=dict(method=['GET']))

        uri = path + '/meterdesc/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_meter_desc',
                       conditions=dict(method=['GET']))

        uri = path + '/meterdesc/{dpid}/{meter_id}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_meter_desc',
                       conditions=dict(method=['GET']))

        uri = path + '/meter/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_meter_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/meter/{dpid}/{meter_id}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_meter_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/groupfeatures/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_group_features',
                       conditions=dict(method=['GET']))

        uri = path + '/groupdesc/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_group_desc',
                       conditions=dict(method=['GET']))

        uri = path + '/groupdesc/{dpid}/{group_id}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
get_group_desc',
                       conditions=dict(method=['GET']))

        uri = path + '/group/{dpid}'
```

```
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_group_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/group/{dpid}/{group_id}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    get_group_stats',
                       conditions=dict(method=['GET']))

        uri = path + '/portdesc/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_port_desc
    ',
                       conditions=dict(method=['GET']))

        uri = path + '/portdesc/{dpid}/{port_no}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_port_desc
    ',
                       conditions=dict(method=['GET']))

        uri = path + '/role/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='get_role',
                       conditions=dict(method=['GET']))

        uri = path + '/flowentry/{cmd}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    mod_flow_entry',
                       conditions=dict(method=['POST']))

        uri = path + '/flowentry/clear/{dpid}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    delete_flow_entry',
                       conditions=dict(method=['DELETE']))

        uri = path + '/meterentry/{cmd}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    mod_meter_entry',
                       conditions=dict(method=['POST']))

        uri = path + '/groupentry/{cmd}'
        mapper.connect('stats', uri,
                       controller=StatsController, action='
    mod_group_entry',
                       conditions=dict(method=['POST']))

        uri = path + '/portdesc/{cmd}'
        mapper.connect('stats', uri,
```

```
                                controller=StatsController, action='mod_port_behavior',
                                conditions=dict(method=['POST']))

        uri = path + '/experimenter/{dpid}'
        mapper.connect('stats', uri,
                                controller=StatsController, action='send_experimenter',
                                conditions=dict(method=['POST']))

        uri = path + '/role'
        mapper.connect('stats', uri,
                                controller=StatsController, action='set_role',
                                conditions=dict(method=['POST']))

    @set_ev_cls([ofp_event.EventOFPStatsReply,
                 ofp_event.EventOFPDescStatsReply,
                 ofp_event.EventOFPFlowStatsReply,
                 ofp_event.EventOFPAggregateStatsReply,
                 ofp_event.EventOFPTableStatsReply,
                 ofp_event.EventOFPTableFeaturesStatsReply,
                 ofp_event.EventOFPPortStatsReply,
                 ofp_event.EventOFPQueueStatsReply,
                 ofp_event.EventOFPQueueDescStatsReply,
                 ofp_event.EventOFPMeterStatsReply,
                 ofp_event.EventOFPMeterFeaturesStatsReply,
                 ofp_event.EventOFPMeterConfigStatsReply,
                 ofp_event.EventOFPGroupStatsReply,
                 ofp_event.EventOFPGroupFeaturesStatsReply,
                 ofp_event.EventOFPGroupDescStatsReply,
                 ofp_event.EventOFPPortDescStatsReply
                 ], MAIN_DISPATCHER)
    def stats_reply_handler(self, ev):
        msg = ev.msg
        dp = msg.datapath

        if dp.id not in self.waiters:
            return
        if msg.xid not in self.waiters[dp.id]:
            return
        lock, msgs = self.waiters[dp.id][msg.xid]
        msgs.append(msg)

        flags = 0
        if dp.ofproto.OFP_VERSION == ofproto_v1_0.OFP_VERSION:
            flags = dp.ofproto.OFPSF_REPLY_MORE
        elif dp.ofproto.OFP_VERSION == ofproto_v1_2.OFP_VERSION:
            flags = dp.ofproto.OFPSF_REPLY_MORE
        elif dp.ofproto.OFP_VERSION >= ofproto_v1_3.OFP_VERSION:
            flags = dp.ofproto.OFPMPF_REPLY_MORE

        if msg.flags & flags:
            return
        del self.waiters[dp.id][msg.xid]
```

```
        lock.set()

    @set_ev_cls([ofp_event.EventOFPSwitchFeatures,
                 ofp_event.EventOFPQueueGetConfigReply,
                 ofp_event.EventOFPRoleReply,
                 ], MAIN_DISPATCHER)
    def features_reply_handler(self, ev):
        msg = ev.msg
        dp = msg.datapath

        if dp.id not in self.waiters:
            return
        if msg.xid not in self.waiters[dp.id]:
            return
        lock, msgs = self.waiters[dp.id][msg.xid]
        msgs.append(msg)

        del self.waiters[dp.id][msg.xid]
        lock.set()
```

A.6 rest_conf_switch.py

```
# Copyright (C) 2012 Nippon Telegraph and Telephone Corporation.
# Copyright (C) 2012 Isaku Yamahata <yamahata at private email ne jp>
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"""
This module provides a set of REST API for switch configuration.
- Per-switch Key-Value store

Used by OpenStack Ryu agent.
"""

import json

from six.moves import http_client

from ryu.app.wsgi import ControllerBase
from ryu.app.wsgi import Response
```

```python
from ryu.base import app_manager
from ryu.controller import conf_switch
from ryu.lib import dpid as dpid_lib


# REST API for switch configuration
#
# get all the switches
# GET /v1.0/conf/switches
#
# get all the configuration keys of a switch
# GET /v1.0/conf/switches/<dpid>
#
# delete all the configuration of a switch
# DELETE /v1.0/conf/switches/<dpid>
#
# set the <key> configuration of a switch
# PUT /v1.0/conf/switches/<dpid>/<key>
#
# get the <key> configuration of a switch
# GET /v1.0/conf/switches/<dpid>/<key>
#
# delete the <key> configuration of a switch
# DELETE /v1.0/conf/switches/<dpid>/<key>
#
# where
# <dpid>: datapath id in 16 hex


class ConfSwitchController(ControllerBase):
    def __init__(self, req, link, data, **config):
        super(ConfSwitchController, self).__init__(req, link, data, **config)
        self.conf_switch = data

    def list_switches(self, _req, **_kwargs):
        dpids = self.conf_switch.dpids()
        body = json.dumps([dpid_lib.dpid_to_str(dpid) for dpid in dpids])
        return Response(content_type='application/json', body=body)

    @staticmethod
    def _do_switch(dpid, func, ret_func):
        dpid = dpid_lib.str_to_dpid(dpid)
        try:
            ret = func(dpid)
        except KeyError:
            return Response(status=http_client.NOT_FOUND,
                            body='no dpid is found %s' %
                            dpid_lib.dpid_to_str(dpid))

        return ret_func(ret)

    def delete_switch(self, _req, dpid, **_kwargs):
```

```
        def _delete_switch(dpid):
            self.conf_switch.del_dpid(dpid)
            return None

        def _ret(_ret):
            return Response(status=http_client.ACCEPTED)

        return self._do_switch(dpid, _delete_switch, _ret)

    def list_keys(self, _req, dpid, **_kwargs):
        def _list_keys(dpid):
            return self.conf_switch.keys(dpid)

        def _ret(keys):
            body = json.dumps(keys)
            return Response(content_type='application/json', body=body)

        return self._do_switch(dpid, _list_keys, _ret)

    @staticmethod
    def _do_key(dpid, key, func, ret_func):
        dpid = dpid_lib.str_to_dpid(dpid)
        try:
            ret = func(dpid, key)
        except KeyError:
            return Response(status=http_client.NOT_FOUND,
                            body='no dpid/key is found %s %s' %
                            (dpid_lib.dpid_to_str(dpid), key))
        return ret_func(ret)

    def set_key(self, req, dpid, key, **_kwargs):
        def _set_val(dpid, key):
            try:
                val = req.json if req.body else {}
            except ValueError:
                return Response(status=http_client.BAD_REQUEST,
                                body='invalid syntax %s' % req.body)
            self.conf_switch.set_key(dpid, key, val)
            return None

        def _ret(_ret):
            return Response(status=http_client.CREATED)

        return self._do_key(dpid, key, _set_val, _ret)

    def get_key(self, _req, dpid, key, **_kwargs):
        def _get_key(dpid, key):
            return self.conf_switch.get_key(dpid, key)

        def _ret(val):
            return Response(content_type='application/json',
                            body=json.dumps(val))

        return self._do_key(dpid, key, _get_key, _ret)
```

```
    def delete_key(self, _req, dpid, key, **_kwargs):
        def _delete_key(dpid, key):
            self.conf_switch.del_key(dpid, key)
            return None

        def _ret(_ret):
            return Response()

        return self._do_key(dpid, key, _delete_key, _ret)


class ConfSwitchAPI(app_manager.RyuApp):
    _CONTEXTS = {
        'conf_switch': conf_switch.ConfSwitchSet,
    }

    def __init__(self, *args, **kwargs):
        super(ConfSwitchAPI, self).__init__(*args, **kwargs)
        self.conf_switch = kwargs['conf_switch']
        wsgi = kwargs['wsgi']
        mapper = wsgi.mapper

        controller = ConfSwitchController
        wsgi.registory[controller.__name__] = self.conf_switch
        route_name = 'conf_switch'
        uri = '/v1.0/conf/switches'
        mapper.connect(route_name, uri, controller=controller,
                       action='list_switches',
                       conditions=dict(method=['GET']))

        uri += '/{dpid}'
        requirements = {'dpid': dpid_lib.DPID_PATTERN}
        s = mapper.submapper(controller=controller, requirements=
    requirements)
        s.connect(route_name, uri, action='delete_switch',
                  conditions=dict(method=['DELETE']))
        s.connect(route_name, uri, action='list_keys',
                  conditions=dict(method=['GET']))

        uri += '/{key}'
        s.connect(route_name, uri, action='set_key',
                  conditions=dict(method=['PUT']))
        s.connect(route_name, uri, action='get_key',
                  conditions=dict(method=['GET']))
        s.connect(route_name, uri, action='delete_key',
                  conditions=dict(method=['DELETE']))
```

A.7 rest_qos.py

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

```
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# limitations under the License.


import logging
import json
import re

from ryu.app import conf_switch_key as cs_key
from ryu.app.wsgi import ControllerBase
from ryu.app.wsgi import Response
from ryu.app.wsgi import route
from ryu.app.wsgi import WSGIApplication
from ryu.base import app_manager
from ryu.controller import conf_switch
from ryu.controller import ofp_event
from ryu.controller import dpset
from ryu.controller.handler import set_ev_cls
from ryu.controller.handler import MAIN_DISPATCHER
from ryu.exception import OFPUnknownVersion
from ryu.lib import dpid as dpid_lib
from ryu.lib import mac
from ryu.lib import ofctl_v1_0
from ryu.lib import ofctl_v1_2
from ryu.lib import ofctl_v1_3
from ryu.lib.ovs import bridge
from ryu.ofproto import ofproto_v1_0
from ryu.ofproto import ofproto_v1_2
from ryu.ofproto import ofproto_v1_3
from ryu.ofproto import ofproto_v1_3_parser
from ryu.ofproto import ether
from ryu.ofproto import inet


# =============================
#            REST API
# =============================
#
#  Note: specify switch and vlan group, as follows.
#   {switch-id} : 'all' or switchID
#   {vlan-id}   : 'all' or vlanID
#
# about queue status
```

```
#
# get status of queue
# GET /qos/queue/status/{switch-id}
#
# about queues
# get a queue configurations
# GET /qos/queue/{switch-id}
#
# set a queue to the switches
# POST /qos/queue/{switch-id}
#
# request body format:
#  {"port_name":"<name of port>",
#   "type": "<linux-htb or linux-other>",
#   "max-rate": "<int>",
#   "queues":[{"max_rate": "<int>", "min_rate": "<int>"},...]}
#
#   Note: This operation override
#         previous configurations.
#   Note: Queue configurations are available for
#         OpenvSwitch.
#   Note: port_name is optional argument.
#         If does not pass the port_name argument,
#         all ports are target for configuration.
#
# delete queue
# DELETE /qos/queue/{swtich-id}
#
#   Note: This operation delete relation of qos record from
#         qos colum in Port table. Therefore,
#         QoS records and Queue records will remain.
#
# about qos rules
#
# get rules of qos
# * for no vlan
# GET /qos/rules/{switch-id}
#
# * for specific vlan group
# GET /qos/rules/{switch-id}/{vlan-id}
#
# set a qos rules
#
#   QoS rules will do the processing pipeline,
#   which entries are register the first table (by default table id 0)
#   and process will apply and go to next table.
#
# * for no vlan
# POST /qos/{switch-id}
#
# * for specific vlan group
# POST /qos/{switch-id}/{vlan-id}
#
#  request body format:
```

```
#   {"priority": "<value>",
#    "match": {"<field1>": "<value1>", "<field2>": "<value2>",...},
#    "actions": {"<action1>": "<value1>", "<action2>": "<value2>",...}
#   }
#
#  Description
#    * priority field
#     <value>
#    "0 to 65533"
#
#   Note: When "priority" has not been set up,
#         "priority: 1" is set to "priority".
#
#    * match field
#     <field> : <value>
#    "in_port" : "<int>"
#    "dl_src"  : "<xx:xx:xx:xx:xx:xx>"
#    "dl_dst"  : "<xx:xx:xx:xx:xx:xx>"
#    "dl_type" : "<ARP or IPv4 or IPv6>"
#    "nw_src"  : "<A.B.C.D/M>"
#    "nw_dst"  : "<A.B.C.D/M>"
#    "ipv6_src": "<xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx/M>"
#    "ipv6_dst": "<xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx:xxxx/M>"
#    "nw_proto": "<TCP or UDP or ICMP or ICMPv6>"
#    "tp_src"  : "<int>"
#    "tp_dst"  : "<int>"
#    "ip_dscp" : "<int>"
#
#    * actions field
#     <field> : <value>
#    "mark": <dscp-value>
#    sets the IPv4 ToS/DSCP field to tos.
#    "meter": <meter-id>
#    apply meter entry
#    "queue": <queue-id>
#    register queue specified by queue-id
#
#   Note: When "actions" has not been set up,
#         "queue: 0" is set to "actions".
#
# delete a qos rules
# * for no vlan
# DELETE /qos/rule/{switch-id}
#
# * for specific vlan group
# DELETE /qos/{switch-id}/{vlan-id}
#
#  request body format:
#   {"<field>":"<value>"}
#
#     <field>  : <value>
#    "qos_id" : "<int>" or "all"
#
# about meter entries
```

```
#
# set a meter entry
# POST /qos/meter/{switch-id}
#
#  request body format:
#   {"meter_id": <int>,
#    "bands":[{"action": "<DROP or DSCP_REMARK>",
#              "flag": "<KBPS or PKTPS or BURST or STATS"
#              "burst_size": <int>,
#              "rate": <int>,
#              "prec_level": <int>},...]}
#
# delete a meter entry
# DELETE /qos/meter/{switch-id}
#
#  request body format:
#   {"<field>":"<value>"}
#
#     <field>  : <value>
#    "meter_id" : "<int>"
#


SWITCHID_PATTERN = dpid_lib.DPID_PATTERN + r'|all'
VLANID_PATTERN = r'[0-9]{1,4}|all'

QOS_TABLE_ID = 0

REST_ALL = 'all'
REST_SWITCHID = 'switch_id'
REST_COMMAND_RESULT = 'command_result'
REST_PRIORITY = 'priority'
REST_VLANID = 'vlan_id'
REST_PORT_NAME = 'port_name'
REST_QUEUE_TYPE = 'type'
REST_QUEUE_MAX_RATE = 'max_rate'
REST_QUEUE_MIN_RATE = 'min_rate'
REST_QUEUES = 'queues'
REST_QOS = 'qos'
REST_QOS_ID = 'qos_id'
REST_COOKIE = 'cookie'

REST_MATCH = 'match'
REST_IN_PORT = 'in_port'
REST_SRC_MAC = 'dl_src'
REST_DST_MAC = 'dl_dst'
REST_DL_TYPE = 'dl_type'
REST_DL_TYPE_ARP = 'ARP'
REST_DL_TYPE_IPV4 = 'IPv4'
REST_DL_TYPE_IPV6 = 'IPv6'
REST_DL_VLAN = 'dl_vlan'
REST_SRC_IP = 'nw_src'
REST_DST_IP = 'nw_dst'
REST_SRC_IPV6 = 'ipv6_src'
```

```
REST_DST_IPV6 = 'ipv6_dst'
REST_NW_PROTO = 'nw_proto'
REST_NW_PROTO_TCP = 'TCP'
REST_NW_PROTO_UDP = 'UDP'
REST_NW_PROTO_ICMP = 'ICMP'
REST_NW_PROTO_ICMPV6 = 'ICMPv6'
REST_TP_SRC = 'tp_src'
REST_TP_DST = 'tp_dst'
REST_DSCP = 'ip_dscp'

REST_ACTION = 'actions'
REST_ACTION_QUEUE = 'queue'
REST_ACTION_MARK = 'mark'
REST_ACTION_METER = 'meter'

REST_METER_ID = 'meter_id'
REST_METER_BURST_SIZE = 'burst_size'
REST_METER_RATE = 'rate'
REST_METER_PREC_LEVEL = 'prec_level'
REST_METER_BANDS = 'bands'
REST_METER_ACTION_DROP = 'drop'
REST_METER_ACTION_REMARK = 'remark'

DEFAULT_FLOW_PRIORITY = 0
QOS_PRIORITY_MAX = ofproto_v1_3_parser.UINT16_MAX - 1
QOS_PRIORITY_MIN = 1

VLANID_NONE = 0
VLANID_MIN = 2
VLANID_MAX = 4094
COOKIE_SHIFT_VLANID = 32

BASE_URL = '/qos'
REQUIREMENTS = {'switchid': SWITCHID_PATTERN,
                'vlanid': VLANID_PATTERN}

LOG = logging.getLogger(__name__)


class RestQoSAPI(app_manager.RyuApp):

    OFP_VERSIONS = [ofproto_v1_0.OFP_VERSION,
                    ofproto_v1_2.OFP_VERSION,
                    ofproto_v1_3.OFP_VERSION]

    _CONTEXTS = {
        'dpset': dpset.DPSet,
        'conf_switch': conf_switch.ConfSwitchSet,
        'wsgi': WSGIApplication}

    def __init__(self, *args, **kwargs):
        super(RestQoSAPI, self).__init__(*args, **kwargs)

        # logger configure
```

```
        QoSController.set_logger(self.logger)
        self.cs = kwargs['conf_switch']
        self.dpset = kwargs['dpset']
        wsgi = kwargs['wsgi']
        self.waiters = {}
        self.data = {}
        self.data['dpset'] = self.dpset
        self.data['waiters'] = self.waiters
        wsgi.registory['QoSController'] = self.data
        wsgi.register(QoSController, self.data)

    def stats_reply_handler(self, ev):
        msg = ev.msg
        dp = msg.datapath

        if dp.id not in self.waiters:
            return
        if msg.xid not in self.waiters[dp.id]:
            return
        lock, msgs = self.waiters[dp.id][msg.xid]
        msgs.append(msg)

        flags = 0
        if dp.ofproto.OFP_VERSION == ofproto_v1_0.OFP_VERSION or \
                dp.ofproto.OFP_VERSION == ofproto_v1_2.OFP_VERSION:
            flags = dp.ofproto.OFPSF_REPLY_MORE
        elif dp.ofproto.OFP_VERSION == ofproto_v1_3.OFP_VERSION:
            flags = dp.ofproto.OFPMPF_REPLY_MORE

        if msg.flags & flags:
            return
        del self.waiters[dp.id][msg.xid]
        lock.set()

    @set_ev_cls(conf_switch.EventConfSwitchSet)
    def conf_switch_set_handler(self, ev):
        if ev.key == cs_key.OVSDB_ADDR:
            QoSController.set_ovsdb_addr(ev.dpid, ev.value)
        else:
            QoSController._LOGGER.debug("unknown event: %s", ev)

    @set_ev_cls(conf_switch.EventConfSwitchDel)
    def conf_switch_del_handler(self, ev):
        if ev.key == cs_key.OVSDB_ADDR:
            QoSController.delete_ovsdb_addr(ev.dpid)
        else:
            QoSController._LOGGER.debug("unknown event: %s", ev)

    @set_ev_cls(dpset.EventDP, dpset.DPSET_EV_DISPATCHER)
    def handler_datapath(self, ev):
        if ev.enter:
            QoSController.regist_ofs(ev.dp, self.CONF)
        else:
            QoSController.unregist_ofs(ev.dp)
```

```python

    # for OpenFlow version1.0
    @set_ev_cls(ofp_event.EventOFPFlowStatsReply, MAIN_DISPATCHER)
    def stats_reply_handler_v1_0(self, ev):
        self.stats_reply_handler(ev)

    # for OpenFlow version1.2 or later
    @set_ev_cls(ofp_event.EventOFPStatsReply, MAIN_DISPATCHER)
    def stats_reply_handler_v1_2(self, ev):
        self.stats_reply_handler(ev)

    # for OpenFlow version1.2 or later
    @set_ev_cls(ofp_event.EventOFPQueueStatsReply, MAIN_DISPATCHER)
    def queue_stats_reply_handler_v1_2(self, ev):
        self.stats_reply_handler(ev)

    # for OpenFlow version1.2 or later
    @set_ev_cls(ofp_event.EventOFPMeterStatsReply, MAIN_DISPATCHER)
    def meter_stats_reply_handler_v1_2(self, ev):
        self.stats_reply_handler(ev)


class QoSOfsList(dict):

    def __init__(self):
        super(QoSOfsList, self).__init__()

    def get_ofs(self, dp_id):
        if len(self) == 0:
            raise ValueError('qos sw is not connected.')

        dps = {}
        if dp_id == REST_ALL:
            dps = self
        else:
            try:
                dpid = dpid_lib.str_to_dpid(dp_id)
            except:
                raise ValueError('Invalid switchID.')

            if dpid in self:
                dps = {dpid: self[dpid]}
            else:
                msg = 'qos sw is not connected. : switchID=%s' % dp_id
                raise ValueError(msg)

        return dps


class QoSController(ControllerBase):

    _OFS_LIST = QoSOfsList()
    _LOGGER = None

```

```
    def __init__(self, req, link, data, **config):
        super(QoSController, self).__init__(req, link, data, **config)
        self.dpset = data['dpset']
        self.waiters = data['waiters']

    @classmethod
    def set_logger(cls, logger):
        cls._LOGGER = logger
        cls._LOGGER.propagate = False
        hdlr = logging.StreamHandler()
        fmt_str = '[QoS][%(levelname)s] %(message)s'
        hdlr.setFormatter(logging.Formatter(fmt_str))
        cls._LOGGER.addHandler(hdlr)

    @staticmethod
    def regist_ofs(dp, CONF):
        if dp.id in QoSController._OFS_LIST:
            return

        dpid_str = dpid_lib.dpid_to_str(dp.id)
        try:
            f_ofs = QoS(dp, CONF)
            f_ofs.set_default_flow()
        except OFPUnknownVersion as message:
            QoSController._LOGGER.info('dpid=%s: %s',
                                       dpid_str, message)
            return

        QoSController._OFS_LIST.setdefault(dp.id, f_ofs)
        QoSController._LOGGER.info('dpid=%s: Join qos switch.',
                                   dpid_str)

    @staticmethod
    def unregist_ofs(dp):
        if dp.id in QoSController._OFS_LIST:
            del QoSController._OFS_LIST[dp.id]
            QoSController._LOGGER.info('dpid=%s: Leave qos switch.',
                                       dpid_lib.dpid_to_str(dp.id))

    @staticmethod
    def set_ovsdb_addr(dpid, value):
        ofs = QoSController._OFS_LIST.get(dpid, None)
        if ofs is not None:
            ofs.set_ovsdb_addr(dpid, value)

    @staticmethod
    def delete_ovsdb_addr(dpid):
        ofs = QoSController._OFS_LIST.get(dpid, None)
        ofs.set_ovsdb_addr(dpid, None)

    @route('qos_switch', BASE_URL + '/queue/{switchid}',
           methods=['GET'], requirements=REQUIREMENTS)
    def get_queue(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
```

```
                                        'get_queue', None)

    @route('qos_switch', BASE_URL + '/queue/{switchid}',
           methods=['POST'], requirements=REQUIREMENTS)
    def set_queue(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                        'set_queue', None)

    @route('qos_switch', BASE_URL + '/queue/{switchid}',
           methods=['DELETE'], requirements=REQUIREMENTS)
    def delete_queue(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                        'delete_queue', None)

    @route('qos_switch', BASE_URL + '/queue/status/{switchid}',
           methods=['GET'], requirements=REQUIREMENTS)
    def get_status(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                        'get_status', self.waiters)

    @route('qos_switch', BASE_URL + '/rules/{switchid}',
           methods=['GET'], requirements=REQUIREMENTS)
    def get_qos(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                        'get_qos', self.waiters)

    @route('qos_switch', BASE_URL + '/rules/{switchid}/{vlanid}',
           methods=['GET'], requirements=REQUIREMENTS)
    def get_vlan_qos(self, req, switchid, vlanid, **_kwargs):
        return self._access_switch(req, switchid, vlanid,
                                        'get_qos', self.waiters)

    @route('qos_switch', BASE_URL + '/rules/{switchid}',
           methods=['POST'], requirements=REQUIREMENTS)
    def set_qos(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                        'set_qos', self.waiters)

    @route('qos_switch', BASE_URL + '/rules/{switchid}/{vlanid}',
           methods=['POST'], requirements=REQUIREMENTS)
    def set_vlan_qos(self, req, switchid, vlanid, **_kwargs):
        return self._access_switch(req, switchid, vlanid,
                                        'set_qos', self.waiters)

    @route('qos_switch', BASE_URL + '/rules/{switchid}',
           methods=['DELETE'], requirements=REQUIREMENTS)
    def delete_qos(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                        'delete_qos', self.waiters)

    @route('qos_switch', BASE_URL + '/rules/{switchid}/{vlanid}',
           methods=['DELETE'], requirements=REQUIREMENTS)
    def delete_vlan_qos(self, req, switchid, vlanid, **_kwargs):
        return self._access_switch(req, switchid, vlanid,
```

```
                                   'delete_qos', self.waiters)

    @route('qos_switch', BASE_URL + '/meter/{switchid}',
           methods=['GET'], requirements=REQUIREMENTS)
    def get_meter(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                   'get_meter', self.waiters)

    @route('qos_switch', BASE_URL + '/meter/{switchid}',
           methods=['POST'], requirements=REQUIREMENTS)
    def set_meter(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                   'set_meter', self.waiters)

    @route('qos_switch', BASE_URL + '/meter/{switchid}',
           methods=['DELETE'], requirements=REQUIREMENTS)
    def delete_meter(self, req, switchid, **_kwargs):
        return self._access_switch(req, switchid, VLANID_NONE,
                                   'delete_meter', self.waiters)

    def _access_switch(self, req, switchid, vlan_id, func, waiters):
        try:
            rest = req.json if req.body else {}
        except ValueError:
            QoSController._LOGGER.debug('invalid syntax %s', req.body)
            return Response(status=400)

        try:
            dps = self._OFS_LIST.get_ofs(switchid)
            vid = QoSController._conv_toint_vlanid(vlan_id)
        except ValueError as message:
            return Response(status=400, body=str(message))

        msgs = []
        for f_ofs in dps.values():
            function = getattr(f_ofs, func)
            try:
                if waiters is not None:
                    msg = function(rest, vid, waiters)
                else:
                    msg = function(rest, vid)
            except ValueError as message:
                return Response(status=400, body=str(message))
            msgs.append(msg)

        body = json.dumps(msgs)
        return Response(content_type='application/json', body=body)

    @staticmethod
    def _conv_toint_vlanid(vlan_id):
        if vlan_id != REST_ALL:
            vlan_id = int(vlan_id)
            if (vlan_id != VLANID_NONE and
                    (vlan_id < VLANID_MIN or VLANID_MAX < vlan_id)):
```

```
                msg = 'Invalid {vlan_id} value. Set [%d-%d]' % (
VLANID_MIN,

VLANID_MAX)
                raise ValueError(msg)
        return vlan_id


class QoS(object):

    _OFCTL = {ofproto_v1_0.OFP_VERSION: ofctl_v1_0,
              ofproto_v1_2.OFP_VERSION: ofctl_v1_2,
              ofproto_v1_3.OFP_VERSION: ofctl_v1_3}

    def __init__(self, dp, CONF):
        super(QoS, self).__init__()
        self.vlan_list = {}
        self.vlan_list[VLANID_NONE] = 0  # for VLAN=None
        self.dp = dp
        self.version = dp.ofproto.OFP_VERSION
        self.queue_list = {}
        self.CONF = CONF
        self.ovsdb_addr = None
        self.ovs_bridge = None

        if self.version not in self._OFCTL:
            raise OFPUnknownVersion(version=self.version)

        self.ofctl = self._OFCTL[self.version]

    def set_default_flow(self):
        if self.version == ofproto_v1_0.OFP_VERSION:
            return

        cookie = 0
        priority = DEFAULT_FLOW_PRIORITY
        actions = [{'type': 'GOTO_TABLE',
                    'table_id': QOS_TABLE_ID + 1}]
        flow = self._to_of_flow(cookie=cookie,
                                priority=priority,
                                match={},
                                actions=actions)

        cmd = self.dp.ofproto.OFPFC_ADD
        self.ofctl.mod_flow_entry(self.dp, flow, cmd)

    def set_ovsdb_addr(self, dpid, ovsdb_addr):
        # easy check if the address format valid
        _proto, _host, _port = ovsdb_addr.split(':')

        old_address = self.ovsdb_addr
        if old_address == ovsdb_addr:
            return
        if ovsdb_addr is None:
```

```
            if self.ovs_bridge:
                self.ovs_bridge.del_controller()
                self.ovs_bridge = None
            return
        self.ovsdb_addr = ovsdb_addr
        if self.ovs_bridge is None:
            ovs_bridge = bridge.OVSBridge(self.CONF, dpid, ovsdb_addr)
            self.ovs_bridge = ovs_bridge
            try:
                ovs_bridge.init()
            except:
                raise ValueError('ovsdb addr is not available.')

    def _update_vlan_list(self, vlan_list):
        for vlan_id in self.vlan_list.keys():
            if vlan_id is not VLANID_NONE and vlan_id not in vlan_list:
                del self.vlan_list[vlan_id]

    def _get_cookie(self, vlan_id):
        if vlan_id == REST_ALL:
            vlan_ids = self.vlan_list.keys()
        else:
            vlan_ids = [vlan_id]

        cookie_list = []
        for vlan_id in vlan_ids:
            self.vlan_list.setdefault(vlan_id, 0)
            self.vlan_list[vlan_id] += 1
            self.vlan_list[vlan_id] &= ofproto_v1_3_parser.UINT32_MAX
            cookie = (vlan_id << COOKIE_SHIFT_VLANID) + \
                self.vlan_list[vlan_id]
            cookie_list.append([cookie, vlan_id])

        return cookie_list

    @staticmethod
    def _cookie_to_qosid(cookie):
        return cookie & ofproto_v1_3_parser.UINT32_MAX

    # REST command template
    def rest_command(func):
        def _rest_command(*args, **kwargs):
            key, value = func(*args, **kwargs)
            switch_id = dpid_lib.dpid_to_str(args[0].dp.id)
            return {REST_SWITCHID: switch_id,
                    key: value}
        return _rest_command

    @rest_command
    def get_status(self, req, vlan_id, waiters):
        if self.version == ofproto_v1_0.OFP_VERSION:
            raise ValueError('get_status operation is not supported')

        msgs = self.ofctl.get_queue_stats(self.dp, waiters)
```

```
        return REST_COMMAND_RESULT, msgs

    @rest_command
    def get_queue(self, rest, vlan_id):
        if len(self.queue_list):
            msg = {'result': 'success',
                   'details': self.queue_list}
        else:
            msg = {'result': 'failure',
                   'details': 'Queue is not exists.'}

        return REST_COMMAND_RESULT, msg

    @rest_command
    def set_queue(self, rest, vlan_id):
        if self.ovs_bridge is None:
            msg = {'result': 'failure',
                   'details': 'ovs_bridge is not exists'}
            return REST_COMMAND_RESULT, msg

        self.queue_list.clear()
        queue_type = rest.get(REST_QUEUE_TYPE, 'linux-htb')
        parent_max_rate = rest.get(REST_QUEUE_MAX_RATE, None)
        queues = rest.get(REST_QUEUES, [])
        queue_id = 0
        queue_config = []
        for queue in queues:
            max_rate = queue.get(REST_QUEUE_MAX_RATE, None)
            min_rate = queue.get(REST_QUEUE_MIN_RATE, None)
            if max_rate is None and min_rate is None:
                raise ValueError('Required to specify max_rate or min_rate')
            config = {}
            if max_rate is not None:
                config['max-rate'] = max_rate
            if min_rate is not None:
                config['min-rate'] = min_rate
            if len(config):
                queue_config.append(config)
            self.queue_list[queue_id] = {'config': config}
            queue_id += 1

        port_name = rest.get(REST_PORT_NAME, None)
        vif_ports = self.ovs_bridge.get_port_name_list()

        if port_name is not None:
            if port_name not in vif_ports:
                raise ValueError('%s port is not exists' % port_name)
            vif_ports = [port_name]

        for port_name in vif_ports:
            try:
                self.ovs_bridge.set_qos(port_name, type=queue_type,
                                        max_rate=parent_max_rate,
```

```
                                        queues=queue_config)
            except Exception as msg:
                raise ValueError(msg)

        msg = {'result': 'success',
               'details': self.queue_list}

        return REST_COMMAND_RESULT, msg

    def _delete_queue(self):
        if self.ovs_bridge is None:
            return False

        vif_ports = self.ovs_bridge.get_external_ports()
        for port in vif_ports:
            self.ovs_bridge.del_qos(port.port_name)
        return True

    @rest_command
    def delete_queue(self, rest, vlan_id):
        self.queue_list.clear()
        if self._delete_queue():
            msg = 'success'
        else:
            msg = 'failure'

        return REST_COMMAND_RESULT, msg

    @rest_command
    def set_qos(self, rest, vlan_id, waiters):
        msgs = []
        cookie_list = self._get_cookie(vlan_id)
        for cookie, vid in cookie_list:
            msg = self._set_qos(cookie, rest, waiters, vid)
            msgs.append(msg)
        return REST_COMMAND_RESULT, msgs

    def _set_qos(self, cookie, rest, waiters, vlan_id):
        match_value = rest[REST_MATCH]
        if vlan_id:
            match_value[REST_DL_VLAN] = vlan_id

        priority = int(rest.get(REST_PRIORITY, QOS_PRIORITY_MIN))
        if (QOS_PRIORITY_MAX < priority):
            raise ValueError('Invalid priority value. Set [%d-%d]'
                             % (QOS_PRIORITY_MIN, QOS_PRIORITY_MAX))

        match = Match.to_openflow(match_value)

        actions = []
        action = rest.get(REST_ACTION, None)
        if action is not None:
            if REST_ACTION_MARK in action:
                actions.append({'type': 'SET_FIELD',
```

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                                    'field': REST_DSCP,
                                    'value': int(action[REST_ACTION_MARK])})
                if REST_ACTION_METER in action:
                    actions.append({'type': 'METER',
                                    'meter_id': action[REST_ACTION_METER]})
                if REST_ACTION_QUEUE in action:
                    actions.append({'type': 'SET_QUEUE',
                                    'queue_id': action[REST_ACTION_QUEUE]})
        else:
            actions.append({'type': 'SET_QUEUE',
                            'queue_id': 0})

        actions.append({'type': 'GOTO_TABLE',
                        'table_id': QOS_TABLE_ID + 1})
        flow = self._to_of_flow(cookie=cookie, priority=priority,
                                match=match, actions=actions)

        cmd = self.dp.ofproto.OFPFC_ADD
        try:
            self.ofctl.mod_flow_entry(self.dp, flow, cmd)
        except:
            raise ValueError('Invalid rule parameter.')

        qos_id = QoS._cookie_to_qosid(cookie)
        msg = {'result': 'success',
               'details': 'QoS added. : qos_id=%d' % qos_id}

        if vlan_id != VLANID_NONE:
            msg.setdefault(REST_VLANID, vlan_id)
        return msg

    @rest_command
    def get_qos(self, rest, vlan_id, waiters):
        rules = {}
        msgs = self.ofctl.get_flow_stats(self.dp, waiters)
        if str(self.dp.id) in msgs:
            flow_stats = msgs[str(self.dp.id)]
            for flow_stat in flow_stats:
                if flow_stat['table_id'] != QOS_TABLE_ID:
                    continue
                priority = flow_stat[REST_PRIORITY]
                if priority != DEFAULT_FLOW_PRIORITY:
                    vid = flow_stat[REST_MATCH].get(REST_DL_VLAN, VLANID_NONE)
                    if vlan_id == REST_ALL or vlan_id == vid:
                        rule = self._to_rest_rule(flow_stat)
                        rules.setdefault(vid, [])
                        rules[vid].append(rule)

        get_data = []
        for vid, rule in rules.items():
            if vid == VLANID_NONE:
                vid_data = {REST_QOS: rule}
            else:
```

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                vid_data = {REST_VLANID: vid, REST_QOS: rule}
            get_data.append(vid_data)

        return REST_COMMAND_RESULT, get_data

    @rest_command
    def delete_qos(self, rest, vlan_id, waiters):
        try:
            if rest[REST_QOS_ID] == REST_ALL:
                qos_id = REST_ALL
            else:
                qos_id = int(rest[REST_QOS_ID])
        except:
            raise ValueError('Invalid qos id.')

        vlan_list = []
        delete_list = []

        msgs = self.ofctl.get_flow_stats(self.dp, waiters)
        if str(self.dp.id) in msgs:
            flow_stats = msgs[str(self.dp.id)]
            for flow_stat in flow_stats:
                cookie = flow_stat[REST_COOKIE]
                ruleid = QoS._cookie_to_qosid(cookie)
                priority = flow_stat[REST_PRIORITY]
                dl_vlan = flow_stat[REST_MATCH].get(REST_DL_VLAN, VLANID_NONE)

                if priority != DEFAULT_FLOW_PRIORITY:
                    if ((qos_id == REST_ALL or qos_id == ruleid) and
                            (vlan_id == dl_vlan or vlan_id == REST_ALL)):
                        match = Match.to_mod_openflow(flow_stat[REST_MATCH])
                        delete_list.append([cookie, priority, match])
                    else:
                        if dl_vlan not in vlan_list:
                            vlan_list.append(dl_vlan)

        self._update_vlan_list(vlan_list)

        if len(delete_list) == 0:
            msg_details = 'QoS rule is not exist.'
            if qos_id != REST_ALL:
                msg_details += ' : QoS ID=%d' % qos_id
            msg = {'result': 'failure',
                   'details': msg_details}
        else:
            cmd = self.dp.ofproto.OFPFC_DELETE_STRICT
            actions = []
            delete_ids = {}
            for cookie, priority, match in delete_list:
                flow = self._to_of_flow(cookie=cookie, priority=priority,
```

```
                                        match=match, actions=actions)
                self.ofctl.mod_flow_entry(self.dp, flow, cmd)

                vid = match.get(REST_DL_VLAN, VLANID_NONE)
                rule_id = QoS._cookie_to_qosid(cookie)
                delete_ids.setdefault(vid, '')
                delete_ids[vid] += (('%d' if delete_ids[vid] == ''
                                     else ',%d') % rule_id)

            msg = []
            for vid, rule_ids in delete_ids.items():
                del_msg = {'result': 'success',
                           'details': ' deleted. : QoS ID=%s' % rule_ids
   }
                if vid != VLANID_NONE:
                    del_msg.setdefault(REST_VLANID, vid)
                msg.append(del_msg)

        return REST_COMMAND_RESULT, msg

    @rest_command
    def set_meter(self, rest, vlan_id, waiters):
        if self.version == ofproto_v1_0.OFP_VERSION:
            raise ValueError('set_meter operation is not supported')

        msgs = []
        msg = self._set_meter(rest, waiters)
        msgs.append(msg)
        return REST_COMMAND_RESULT, msgs

    def _set_meter(self, rest, waiters):
        cmd = self.dp.ofproto.OFPMC_ADD
        try:
            self.ofctl.mod_meter_entry(self.dp, rest, cmd)
        except:
            raise ValueError('Invalid meter parameter.')

        msg = {'result': 'success',
               'details': 'Meter added. : Meter ID=%s' %
               rest[REST_METER_ID]}
        return msg

    @rest_command
    def get_meter(self, rest, vlan_id, waiters):
        if (self.version == ofproto_v1_0.OFP_VERSION or
                self.version == ofproto_v1_2.OFP_VERSION):
            raise ValueError('get_meter operation is not supported')

        msgs = self.ofctl.get_meter_stats(self.dp, waiters)
        return REST_COMMAND_RESULT, msgs

    @rest_command
    def delete_meter(self, rest, vlan_id, waiters):
        if (self.version == ofproto_v1_0.OFP_VERSION or
```

```
                self.version == ofproto_v1_2.OFP_VERSION):
            raise ValueError('delete_meter operation is not supported')

        cmd = self.dp.ofproto.OFPMC_DELETE
        try:
            self.ofctl.mod_meter_entry(self.dp, rest, cmd)
        except:
            raise ValueError('Invalid meter parameter.')

        msg = {'result': 'success',
               'details': 'Meter deleted. : Meter ID=%s' %
               rest[REST_METER_ID]}
        return REST_COMMAND_RESULT, msg

    def _to_of_flow(self, cookie, priority, match, actions):
        flow = {'cookie': cookie,
                'priority': priority,
                'flags': 0,
                'idle_timeout': 0,
                'hard_timeout': 0,
                'match': match,
                'actions': actions}
        return flow

    def _to_rest_rule(self, flow):
        ruleid = QoS._cookie_to_qosid(flow[REST_COOKIE])
        rule = {REST_QOS_ID: ruleid}
        rule.update({REST_PRIORITY: flow[REST_PRIORITY]})
        rule.update(Match.to_rest(flow))
        rule.update(Action.to_rest(flow))
        return rule


class Match(object):

    _CONVERT = {REST_DL_TYPE:
                {REST_DL_TYPE_ARP: ether.ETH_TYPE_ARP,
                 REST_DL_TYPE_IPV4: ether.ETH_TYPE_IP,
                 REST_DL_TYPE_IPV6: ether.ETH_TYPE_IPV6},
                REST_NW_PROTO:
                {REST_NW_PROTO_TCP: inet.IPPROTO_TCP,
                 REST_NW_PROTO_UDP: inet.IPPROTO_UDP,
                 REST_NW_PROTO_ICMP: inet.IPPROTO_ICMP,
                 REST_NW_PROTO_ICMPV6: inet.IPPROTO_ICMPV6}}

    @staticmethod
    def to_openflow(rest):

        def __inv_combi(msg):
            raise ValueError('Invalid combination: [%s]' % msg)

        def __inv_2and1(*args):
            __inv_combi('%s=%s and %s' % (args[0], args[1], args[2]))

```

```
        def __inv_2and2(*args):
            __inv_combi('%s=%s and %s=%s' % (
                args[0], args[1], args[2], args[3]))

        def __inv_1and1(*args):
            __inv_combi('%s and %s' % (args[0], args[1]))

        def __inv_1and2(*args):
            __inv_combi('%s and %s=%s' % (args[0], args[1], args[2]))

        match = {}

        # error check
        dl_type = rest.get(REST_DL_TYPE)
        nw_proto = rest.get(REST_NW_PROTO)
        if dl_type is not None:
            if dl_type == REST_DL_TYPE_ARP:
                if REST_SRC_IPV6 in rest:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_ARP, REST_SRC_IPV6)
                if REST_DST_IPV6 in rest:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_ARP, REST_DST_IPV6)
                if REST_DSCP in rest:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_ARP, REST_DSCP)
                if nw_proto:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_ARP, REST_NW_PROTO)
            elif dl_type == REST_DL_TYPE_IPV4:
                if REST_SRC_IPV6 in rest:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_IPV4, REST_SRC_IPV6)
                if REST_DST_IPV6 in rest:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_IPV4, REST_DST_IPV6)
                if nw_proto == REST_NW_PROTO_ICMPV6:
                    __inv_2and2(
                        REST_DL_TYPE, REST_DL_TYPE_IPV4,
                        REST_NW_PROTO, REST_NW_PROTO_ICMPV6)
            elif dl_type == REST_DL_TYPE_IPV6:
                if REST_SRC_IP in rest:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_IPV6, REST_SRC_IP)
                if REST_DST_IP in rest:
                    __inv_2and1(
                        REST_DL_TYPE, REST_DL_TYPE_IPV6, REST_DST_IP)
                if nw_proto == REST_NW_PROTO_ICMP:
                    __inv_2and2(
                        REST_DL_TYPE, REST_DL_TYPE_IPV6,
                        REST_NW_PROTO, REST_NW_PROTO_ICMP)
            else:
                raise ValueError('Unknown dl_type : %s' % dl_type)
        else:
```

```
            if REST_SRC_IP in rest:
                if REST_SRC_IPV6 in rest:
                    __inv_1and1(REST_SRC_IP, REST_SRC_IPV6)
                if REST_DST_IPV6 in rest:
                    __inv_1and1(REST_SRC_IP, REST_DST_IPV6)
                if nw_proto == REST_NW_PROTO_ICMPV6:
                    __inv_1and2(
                        REST_SRC_IP, REST_NW_PROTO, REST_NW_PROTO_ICMPV6
)
                rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
            elif REST_DST_IP in rest:
                if REST_SRC_IPV6 in rest:
                    __inv_1and1(REST_DST_IP, REST_SRC_IPV6)
                if REST_DST_IPV6 in rest:
                    __inv_1and1(REST_DST_IP, REST_DST_IPV6)
                if nw_proto == REST_NW_PROTO_ICMPV6:
                    __inv_1and2(
                        REST_DST_IP, REST_NW_PROTO, REST_NW_PROTO_ICMPV6
)
                rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
            elif REST_SRC_IPV6 in rest:
                if nw_proto == REST_NW_PROTO_ICMP:
                    __inv_1and2(
                        REST_SRC_IPV6, REST_NW_PROTO, REST_NW_PROTO_ICMP
)
                rest[REST_DL_TYPE] = REST_DL_TYPE_IPV6
            elif REST_DST_IPV6 in rest:
                if nw_proto == REST_NW_PROTO_ICMP:
                    __inv_1and2(
                        REST_DST_IPV6, REST_NW_PROTO, REST_NW_PROTO_ICMP
)
                rest[REST_DL_TYPE] = REST_DL_TYPE_IPV6
            elif REST_DSCP in rest:
                # Apply dl_type ipv4, if doesn't specify dl_type
                rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
            else:
                if nw_proto == REST_NW_PROTO_ICMP:
                    rest[REST_DL_TYPE] = REST_DL_TYPE_IPV4
                elif nw_proto == REST_NW_PROTO_ICMPV6:
                    rest[REST_DL_TYPE] = REST_DL_TYPE_IPV6
                elif nw_proto == REST_NW_PROTO_TCP or \
                        nw_proto == REST_NW_PROTO_UDP:
                    raise ValueError('no dl_type was specified')
                else:
                    raise ValueError('Unknown nw_proto: %s' % nw_proto)

        for key, value in rest.items():
            if key in Match._CONVERT:
                if value in Match._CONVERT[key]:
                    match.setdefault(key, Match._CONVERT[key][value])
                else:
                    raise ValueError('Invalid rule parameter. : key=%s'
% key)
            else:
```

```
            match.setdefault(key, value)

    return match

@staticmethod
def to_rest(openflow):
    of_match = openflow[REST_MATCH]

    mac_dontcare = mac.haddr_to_str(mac.DONTCARE)
    ip_dontcare = '0.0.0.0'
    ipv6_dontcare = '::'

    match = {}
    for key, value in of_match.items():
        if key == REST_SRC_MAC or key == REST_DST_MAC:
            if value == mac_dontcare:
                continue
        elif key == REST_SRC_IP or key == REST_DST_IP:
            if value == ip_dontcare:
                continue
        elif key == REST_SRC_IPV6 or key == REST_DST_IPV6:
            if value == ipv6_dontcare:
                continue
        elif value == 0:
            continue

        if key in Match._CONVERT:
            conv = Match._CONVERT[key]
            conv = dict((value, key) for key, value in conv.items())
            match.setdefault(key, conv[value])
        else:
            match.setdefault(key, value)

    return match

@staticmethod
def to_mod_openflow(of_match):
    mac_dontcare = mac.haddr_to_str(mac.DONTCARE)
    ip_dontcare = '0.0.0.0'
    ipv6_dontcare = '::'

    match = {}
    for key, value in of_match.items():
        if key == REST_SRC_MAC or key == REST_DST_MAC:
            if value == mac_dontcare:
                continue
        elif key == REST_SRC_IP or key == REST_DST_IP:
            if value == ip_dontcare:
                continue
        elif key == REST_SRC_IPV6 or key == REST_DST_IPV6:
            if value == ipv6_dontcare:
                continue
        elif value == 0:
            continue
```

```
            match.setdefault(key, value)

        return match


class Action(object):

    @staticmethod
    def to_rest(flow):
        if REST_ACTION in flow:
            actions = []
            for act in flow[REST_ACTION]:
                field_value = re.search('SET_FIELD: \{ip_dscp:(\d+)',
    act)
                if field_value:
                    actions.append({REST_ACTION_MARK: field_value.group
    (1)})
                meter_value = re.search('METER:(\d+)', act)
                if meter_value:
                    actions.append({REST_ACTION_METER: meter_value.group
    (1)})
                queue_value = re.search('SET_QUEUE:(\d+)', act)
                if queue_value:
                    actions.append({REST_ACTION_QUEUE: queue_value.group
    (1)})
            action = {REST_ACTION: actions}
        else:
            action = {REST_ACTION: 'Unknown action type.'}

        return action
```

A.8 Topology_qos_TRAFFIC_GEN.py

```
from mininet.net import Mininet
from mininet.node import Controller, RemoteController, OVSController
from mininet.node import CPULimitedHost, Host, Node
from mininet.node import OVSKernelSwitch, UserSwitch
from mininet.node import IVSSwitch
from mininet.cli import CLI
from mininet.log import setLogLevel, info
from mininet.link import TCLink, Intf
from subprocess import call
import threading
import subprocess
import random
import os
import time
import datetime
import json
import sys
```

```
import ditg

from Controller_commands import *


def myNetwork():
    max_rate_queue=100#Mbps
    max_rate_queue=max_rate_queue*1000000
    Default=str(max_rate_queue*20/100)#20%
    Premium=str(max_rate_queue*80/100)#80%
    Gold=str(max_rate_queue*100/100)#100%

    change_values=6#change every number*5 minutes
    Q0=False
    #Stress Queue 1 (2,4,6,7)
    Q1=False
    #Stress Queue 2 (5)
    Q2=False
    #moltiplicator initialization
    F0_max=2
    F1_max=300
    F2_max=300
    F0=1
    F1=1
    F2=1

    net=Mininet( topo=None,
                 build=False,
                 ipBase='10.0.0.0/8')

    info( '***Adding controller\n')
    c0=net.addController(name='c0',
                         controller=RemoteController,
                         ip='127.0.0.1',
                         protocol='tcp',
                         port=6633)

    info( '***Adding switches\n')
    s1 = net.addSwitch('s1',dpid='0000000000000001',protocols="
    OpenFlow13")
    s2 = net.addSwitch('s2',dpid='0000000000000002',protocols="
    OpenFlow13")

    info( '***Adding Host\n')
    h0 = net.addHost('h0', ip='10.10/24', mac='00:00:00:00:00:0a')
    h1 = net.addHost('h1', ip='10.11/24', mac='00:00:00:00:00:0b')
    h2 = net.addHost('h2', ip='10.12/24', mac='00:00:00:00:00:0c')
    h3 = net.addHost('h3', ip='10.13/24', mac='00:00:00:00:00:0d')
    h4 = net.addHost('h4', ip='10.14/24', mac='00:00:00:00:00:0e')
    h5 = net.addHost('h5', ip='10.15/24', mac='00:00:00:00:00:0f')

    info( '***Adding Link\n')
    net.addLink(s1,s2,2,2)

```

```
    net.addLink(s1, h0,3,0)
    net.addLink(s1, h1,4,0)
    net.addLink(s1, h2,5,0)
    net.addLink(s2, h3,3,0)
    net.addLink(s2, h4,4,0)
    net.addLink(s2, h5,5,0)

    info( '***Starting Network\n')
    net.build()

    info( '***Starting Controllers\n')
    for controller in net.controllers:
        controller.start()

    info( '***Starting Switches\n')
    net.get('s1').start([c0])
    net.get('s2').start([c0])


    #Activation of manager in listening on port 6632
    os.popen("sudo -S ovs-vsctl set-manager ptcp:6632", 'w').write("Ao70pa45")
    time.sleep(2)
    NET = get_switchis()
    if NET != "NO NET" and NET!="[,]":
        i=1
        while i<NET.find("]"):
            mom_NET=NET[i:]
            datapath=NET[i:i+mom_NET.find(",")]
            i=i+mom_NET.find(",")+2
            port_id = switch_ports_name(datapath)
            for k in range(0,len(port_id)):
                if len(port_id[k])<=2:
                    pp=port_id[k]
                    print pp
                    ovssctl_set_bridge(port_id[k])
        time.sleep(0.2)
        i=1
        while i<NET.find("]"):
            mom_NET=NET[i:]
            datapath=NET[i:i+mom_NET.find(",")]
            i=i+mom_NET.find(",")+2
            port_id = switch_ports_name(datapath)
            ovsdb_addr(datapath)
            IP_Flag=True
            for index in range(0,len(port_id)):
                if port_id[index]=="s1-eth2" or port_id[index]=="s2-eth2":
                    set_queue(datapath, port_id[index], str(max_rate_queue), "{\"max_rate\": \""+Default+"\"}, {\"max_rate\": \""+Premium+"\"}, {\"min_rate\": \""+Gold+"\"}")
                    port = port_id[index][port_id[index].find("h")+1:]
                    if port_id[index]=="s1-eth2":
                        IP_Destination="10.0.0.11"
```

```
                    if port_id[index]=="s2-eth2":
                        IP_Destination="10.0.0.13"
                    set_Telecom_queue(datapath, port, IP_Flag, IP_Destination)
            for index in range(0,len(port_id)):
                if port_id[index]=="s1-eth4" or port_id[index]=="s2-eth3":
                    port = port_id[index][port_id[index].find("h")+1:]
                    if port_id[index]=="s1-eth4":
                        IP_Destination="10.0.0.13"
                    if port_id[index]=="s2-eth3":
                        IP_Destination="10.0.0.11"
                    set_Telecom_queue(datapath, port, IP_Flag, IP_Destination)

    # Import CSV data
    print 'Csv Import'
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[0], skiprows=[0]) # serv 0 tx
    time_values = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[1], skiprows=[0]) # serv 0 tx
    serv_0_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[2], skiprows=[0]) # serv 0 rx
    serv_0_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[3], skiprows=[0]) # serv 1 tx
    serv_1_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[4], skiprows=[0]) # serv 1 rx
    serv_1_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[5], skiprows=[0]) # serv 2 tx
    serv_2_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[6], skiprows=[0]) # serv 2 rx
    serv_2_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[15], skiprows=[0]) # serv 3 tx
    serv_3_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[16], skiprows=[0]) # serv 3 rx
    serv_3_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[11], skiprows=[0]) # serv 4 tx
    serv_4_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[12], skiprows=[0]) # serv 4 rx
    serv_4_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[7], skiprows=[0]) # serv 5 tx
    serv_5_tx = serv.values
```

```
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[8], skiprows=[0]) # serv 5 rx
    serv_5_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[9], skiprows=[0]) # serv 6 tx
    serv_6_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[10], skiprows=[0]) # serv 6 rx
    serv_6_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[13], skiprows=[0]) # serv 7 tx
    serv_7_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[14], skiprows=[0]) # serv 7 rx
    serv_7_rx = serv.values

    i = 0
    j = 0
    # pkts
    n = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
    # pkts per second
    avg = [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0]
    F0=F0_max
    F1=1
    F2=1
    print 'Wait for time alignment'
    wait=ditg.TIME/60
    check_time=False
    while check_time==False:
        now=datetime.datetime.now()
        time.sleep(0.1)
        if now.minute%wait==0:
            check_time=True
            if len(str(now.minute))==1:
                starting_time=str(now.hour)+':0'+str(now.minute)
            else:
                starting_time=str(now.hour)+':'+str(now.minute)
            print starting_time
            k=0
            for index in time_values:
                if index==starting_time:
                    i=k
                    break
                k=k+1
    print 'Starting Time: '+str(time_values[i])
    while j < ditg.SIM_N:
        #calculate the moltiplicators

        if Q0:
            if j%change_values==0:
                if F0==1:
                    F0=F0_max
                else:
                    F0=1
```

```
        if Q1:
            if j%change_values==0:
                if F1==1:
                    F1=F1_max
                else:
                    F1=1
        if Q2:
            if j%change_values==0:
                if F2==1:
                    F2=F2_max
                else:
                    F2=1



        # Server start
        print 'Start ITGRecv'
        h1.cmd('ITGRecv &')
        h3.cmd('ITGRecv &')
        time.sleep(2)
        # Sum of packets
        sum_in = 0
        sum_out = 0
        # Serv 0 tx
        n[0] = int(serv_0_tx[i])*F0 / ditg.SCALE + 1
        avg[0] = n[0] / (ditg.TIME-10) + 1
        if avg[0] > 0 and n[0] > 0:
            com = ditg.createCmd_2(dst=ditg.dst,port="10001",tos=ditg.SERV_0,nPkts=str(n[0]),avg=str(avg[0]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[0]

        # Serv 0 rx
        n[0] = int(serv_0_rx[i])*F0 / ditg.SCALE + 1
        avg[0] = n[0] / (ditg.TIME-10) + 1
        if avg[0] > 0 and n[0] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10001",tos=ditg.SERV_0,nPkts=str(n[0]),avg=str(avg[0]))
            print(com)
            h3.cmd(com)
            sum_out = sum_out + n[0]

        # Serv 1 tx
        n[1] = int(serv_1_tx[i])*F0 / ditg.SCALE + 1
        avg[1] = n[1] / (ditg.TIME-10) + 1
        if avg[1] > 0 and n[1] > 0:
            com = ditg.createCmd_2(dst=ditg.dst,port="10002",tos=ditg.SERV_1,nPkts=str(n[1]),avg=str(avg[1]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[1]

        # Serv 1 rx
```

```
        n[1] = int(serv_1_rx[i])*F0 / ditg.SCALE + 1
        avg[1] = n[1] / (ditg.TIME-10) + 1
        if avg[1] > 0 and n[1] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10002",tos=ditg.SERV_1,nPkts=str(n[1]),avg=str(avg[1]))
            print(com)
            h3.cmd(com)
            sum_out = sum_out + n[1]

        # Serv 2 tx
        n[2] = int(serv_2_tx[i])*F1 / ditg.SCALE + 1
        avg[2] = n[2] / (ditg.TIME-10) + 1
        if avg[2] > 0 and n[2] > 0:
            com = ditg.createCmd_2(dst=ditg.dst,port="10003",tos=ditg.SERV_2,nPkts=str(n[2]),avg=str(avg[2]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[2]

        # Serv 2 rx
        n[2] = int(serv_2_rx[i])*F1 / ditg.SCALE + 1
        avg[2] = n[2] / (ditg.TIME-10) + 1
        if avg[2] > 0 and n[2] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10003",tos=ditg.SERV_2,nPkts=str(n[2]),avg=str(avg[2]))
            print(com)
            h3.cmd(com)
            sum_out = sum_out + n[2]

        # Serv 3 tx
        n[3] = int(serv_3_tx[i])*F0 / ditg.SCALE + 1
        avg[3] = n[3] / (ditg.TIME-10) + 1
        if avg[3] > 0 and n[3] > 0:
            com = ditg.createCmd_2(dst=ditg.dst,port="10004",tos=ditg.SERV_3,nPkts=str(n[3]),avg=str(avg[3]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[3]

        # Serv 3 rx
        n[3] = int(serv_3_rx[i])*F0 / ditg.SCALE + 1
        avg[3] = n[3] / (ditg.TIME-10) + 1
        if avg[3] > 0 and n[3] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10004",tos=ditg.SERV_3,nPkts=str(n[3]),avg=str(avg[3]))
            print(com)
            h3.cmd(com)
            sum_out = sum_out + n[3]

        # Serv 4 tx
        n[4] = int(serv_4_tx[i])*F1 / ditg.SCALE + 1
        avg[4] = n[4] / (ditg.TIME-10) + 1
        if avg[4] > 0 and n[4] > 0:
```

```
            com = ditg.createCmd_2(dst=ditg.dst,port="10005",tos=ditg.SERV_4,nPkts=str(n[4]),avg=str(avg[4]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[4]

        # Serv 4 rx
        n[4] = int(serv_4_rx[i])*F1 / ditg.SCALE + 1
        avg[4] = n[4] / (ditg.TIME-10) + 1
        if avg[4] > 0 and n[4] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10005",tos=ditg.SERV_4,nPkts=str(n[4]),avg=str(avg[4]))
            print(com)
            h3.cmd(com)
            sum_out = sum_out + n[4]

        # Serv 5 tx
        n[5] = int(serv_5_tx[i])*F2 / ditg.SCALE + 1
        avg[5] = n[5] / (ditg.TIME-10) + 1
        if avg[5] > 0 and n[5] > 0:
            com = ditg.createCmd_2(dst=ditg.dst,port="10006",tos=ditg.SERV_5,nPkts=str(n[5]),avg=str(avg[5]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[5]

        # Serv 5 rx
        n[5] = int(serv_5_rx[i])*F2 / ditg.SCALE + 1
        avg[5] = n[5] / (ditg.TIME-10) + 1
        if avg[5] > 0 and n[5] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10006",tos=ditg.SERV_5,nPkts=str(n[5]),avg=str(avg[5]))
            print(com)
            h3.cmd(com)
            sum_out = sum_out + n[5]

        # Serv 6 tx
        n[6] = int(serv_6_tx[i])*F1 / ditg.SCALE + 1
        avg[6] = n[6] / (ditg.TIME-10) + 1
        if avg[6] > 0 and n[6] > 0:
            com = ditg.createCmd_2(dst=ditg.dst,port="10007",tos=ditg.SERV_6,nPkts=str(n[6]),avg=str(avg[6]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[6]

        # Serv 6 rx
        n[6] = int(serv_6_rx[i])*F1 / ditg.SCALE + 1
        avg[6] = n[6] / (ditg.TIME-10) + 1
        if avg[6] > 0 and n[6] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10007",tos=ditg.SERV_6,nPkts=str(n[6]),avg=str(avg[6]))
            print(com)
            h3.cmd(com)
```

```
            sum_out = sum_out + n[6]


        # Serv 7 tx
        n[7] = int(serv_7_tx[i])*F1 / ditg.SCALE + 1
        avg[7] = n[7] / (ditg.TIME-10) + 1
        if avg[7] > 0 and n[7] > 0:
            com = ditg.createCmd_2(dst=ditg.dst,port="10008",tos=ditg.SERV_7,nPkts=str(n[7]),avg=str(avg[7]))
            print(com)
            h1.cmd(com)
            sum_in = sum_in + n[7]

        # Serv 7 rx
        n[7] = int(serv_7_rx[i])*F1 / ditg.SCALE + 1
        avg[7] = n[7] / (ditg.TIME-10) + 1
        if avg[7] > 0 and n[7] > 0:
            com = ditg.createCmd_2(dst=ditg.src,port="10008",tos=ditg.SERV_7,nPkts=str(n[7]),avg=str(avg[7]))
            print(com)
            h3.cmd(com)
            sum_out = sum_out + n[7]

        j = j+1
        i=i+1
        if i % ditg.SIZE==0 and i!=0:
            i=0
        print i
        print('Sum of Packets IN: ' + str(sum_in))
        print('Sum of Packets OUT: ' + str(sum_out))

  time.sleep(61)
        check_time=False
        while check_time==False:
            now=datetime.datetime.now()
            if now.minute%wait==0:
                check_time=True
                print "Time: "+str(now)
                print 'Database Time: '+str(time_values[i])
            else:
                time.sleep(1)
        h1.cmd('kill %ITGSend')
        h1.cmd('kill %ITGRecv')
    CLI(net)
    net.stop()

if __name__=='__main__':
    setLogLevel( 'info' )
    myNetwork()
```

A.9 ditg.py

```python
#!/usr/bin/python
import pandas as pd
import time

# Constants
# Value of Interval Time in second
TIME = 300
TIME_MS = TIME * 1000
# Scale factor for the packet rate. It will be equal to [ pkts / scale ] per second.
SCALE = 400
# CSV Entries
SIZE = 576
# Simulation Time in CSV hours
SIM = 720
# Simulation in number of intevals
SIM_N = SIM * 12
computername="jedi"
# CSV File
CSV = '/home/'+computername+'/Scrivania/RyuDatapathMonitor-master/CSV/vlan_interfaccia1_DOS.csv'
# ToS
SERV_0 = "0"
SERV_1 = "32"
SERV_2 = "72"
SERV_3 = "96"
SERV_4 = "136"
SERV_5 = "160"
SERV_6 = "192"
SERV_7 = "224"

# IDT_OPT
# constant
c_idt = "-C"
#poisson
p_idt = "-O"
#esponential
e_idt ="-E"

# PS_OPT
# constant
c_ps = "-c"
# poisson
p_ps = "-o"
# esponential
e_ps ="-e"

# default value for protocol and packet size
DEFAULT_P = "UDP"
DEFAULT_PS = "512"

```

```python
# Host Ip
src = "10.0.0.11"
dst = "10.0.0.13"

# Type of distribution
choice_i = c_idt
choice_s = c_ps


# Cmd creation
def createCmd(src, dst, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=DEFAULT_PS):
    com = 'ITGManager ' + src + ' -a ' + dst + ' -b ' + tos + ' ' + choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t ' + str(TIME_MS-8000)
    return com

# Cmd creation
def createCmd_2(dst, port, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=DEFAULT_PS):
    com = 'ITGSend -a ' + dst + ' -rp ' + str(port) + ' -b ' + tos + ' ' + choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t ' + str(TIME_MS-10000) + ' &'
    return com

# Cmd creation Iperf
def createCmd_3(dst, port, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=DEFAULT_PS):
    com = 'iperf3 -c ' + dst + ' -p ' + str(port) + ' -S ' + tos + ' ' + ' -k ' + str(nPkts) + ' &'
    return com
```

Appendix B

Python Codes For Dedicated Hardware Network Devices

B.1 Traffic_Real_Hwd.py

```python

from subprocess import call
import threading
import subprocess
import random
import os
import time
import datetime
import json
import sys
import ditg
import psutil
import SDL_DS1307


def f1():
    IP_SRC='169.254.207.222'
    IP_DST = "169.254.181.98"
    os.system('sudo ifconfig eth0 '+IP_SRC+' netmask 255.255.0.0')
    ds1307 = SDL_DS1307.SDL_DS1307(1, 0x68)
    time.sleep(2)
    now=ds1307.read_datetime()
    str_time='"'+str(now.year)+'-'+str(now.month)+'-'+str(now.day)+' '+str(now.hour)+':'+str(now.minute)+':'+str(now.second)+'"'
    os.system('sudo date --set '+str_time)

    print ('Csv Import')
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[0], skiprows=[0]) # serv 0 tx
    time_values = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[1], skiprows=[0]) # serv 0 tx
    serv_0_tx = serv.values
```

```
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[2], skiprows
   =[0]) # serv 0 rx
    serv_0_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[3], skiprows
   =[0]) # serv 1 tx
    serv_1_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[4], skiprows
   =[0]) # serv 1 rx
    serv_1_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[5], skiprows
   =[0]) # serv 2 tx
    serv_2_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[6], skiprows
   =[0]) # serv 2 rx
    serv_2_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[15], skiprows
   =[0]) # serv 3 tx
    serv_3_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[16], skiprows
   =[0]) # serv 3 rx
    serv_3_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[11], skiprows
   =[0]) # serv 4 tx
    serv_4_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[12], skiprows
   =[0]) # serv 4 rx
    serv_4_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[7], skiprows
   =[0]) # serv 5 tx
    serv_5_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[8], skiprows
   =[0]) # serv 5 rx
    serv_5_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[9], skiprows
   =[0]) # serv 6 tx
    serv_6_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[10], skiprows
   =[0]) # serv 6 rx
    serv_6_rx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[13], skiprows
   =[0]) # serv 7 tx
    serv_7_tx = serv.values
    serv = ditg.pd.read_csv(ditg.CSV, sep=';', usecols=[14], skiprows
   =[0]) # serv 7 rx
    serv_7_rx = serv.values

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

```
    F1=1
    F2=1
    print ('Wait for time alignment')
    wait=ditg.TIME/60
    check_time=False
    while check_time==False:
        now=datetime.datetime.now()
        time.sleep(0.1)
        try:
            if now.minute%wait==0:
                check_time=True
                if len(str(now.minute))==1:
                    starting_time=str(now.hour)+':0'+str(now.minute)
                else:
                    starting_time=str(now.hour)+':'+str(now.minute)
                print (starting_time)
                k=0
                for index in time_values:
                    if index==starting_time:
                        i=k
                        break
                    k=k+1
            else:
                time.sleep(0.5)
        except:
            time.sleep(0.1)
    print ('Starting Time: '+str(time_values[i]))
    while j < ditg.SIM_N:
        try:
            now=datetime.datetime.now()
            if len(str(now.minute))==1:
                starting_time=str(now.hour)+':0'+str(now.minute)
            else:
                starting_time=str(now.hour)+':'+str(now.minute)

            if starting_time==time_values[1]:
                print (starting_time)
            else:
                k=0
                for index in time_values:
                    if index==starting_time:
                        i=k
                        break
                    k=k+1
        except:
            time.sleep(0.1)
        time.sleep(4)
        # Sum of packets
        sum_in = 0
        sum_out = 0


        # Serv 0 rx
        n[0] = int(serv_0_rx[i])*F0 / ditg.SCALE + 1
```

```python
        avg[0] = n[0] / (ditg.TIME-10) + 1
        if avg[0] > 0 and n[0] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10001",tos=ditg.SERV_0,nPkts=str(n[0]),avg=str(avg[0]))
            print(com)
            os.popen(com)
            sum_out = sum_out + n[0]

        # Serv 1 rx
        n[1] = int(serv_1_rx[i])*F0 / ditg.SCALE + 1
        avg[1] = n[1] / (ditg.TIME-10) + 1
        if avg[1] > 0 and n[1] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10002",tos=ditg.SERV_1,nPkts=str(n[1]),avg=str(avg[1]))
            print(com)
            os.popen(com)
            sum_out = sum_out + n[1]

        # Serv 2 rx
        n[2] = int(serv_2_rx[i])*F1 / ditg.SCALE + 1
        avg[2] = n[2] / (ditg.TIME-10) + 1
        if avg[2] > 0 and n[2] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10003",tos=ditg.SERV_2,nPkts=str(n[2]),avg=str(avg[2]))
            print(com)
            os.popen(com)
            sum_out = sum_out + n[2]

        # Serv 3 rx
        n[3] = int(serv_3_rx[i])*F0 / ditg.SCALE + 1
        avg[3] = n[3] / (ditg.TIME-10) + 1
        if avg[3] > 0 and n[3] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10004",tos=ditg.SERV_3,nPkts=str(n[3]),avg=str(avg[3]))
            print(com)
            os.popen(com)
            sum_out = sum_out + n[3]

        # Serv 4 rx
        n[4] = int(serv_4_rx[i])*F1 / ditg.SCALE + 1
        avg[4] = n[4] / (ditg.TIME-10) + 1
        if avg[4] > 0 and n[4] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10005",tos=ditg.SERV_4,nPkts=str(n[4]),avg=str(avg[4]))
            print(com)
            os.popen(com)
            sum_out = sum_out + n[4]

        # Serv 5 rx
        n[5] = int(serv_5_rx[i])*F2 / ditg.SCALE + 1
        avg[5] = n[5] / (ditg.TIME-10) + 1
        if avg[5] > 0 and n[5] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10006",tos=ditg.SERV_5,nPkts=str(n[5]),avg=str(avg[5]))
```

```
            print(com)
            os.popen(com)
            sum_out = sum_out + n[5]

        # Serv 6 rx
        n[6] = int(serv_6_rx[i])*F1 / ditg.SCALE + 1
        avg[6] = n[6] / (ditg.TIME-10) + 1
        if avg[6] > 0 and n[6] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10007",tos=ditg.SERV_6,nPkts=str(n[6]),avg=str(avg[6]))
            print(com)
            os.popen(com)
            sum_out = sum_out + n[6]

        # Serv 7 rx
        n[7] = int(serv_7_rx[i])*F1 / ditg.SCALE + 1
        avg[7] = n[7] / (ditg.TIME-10) + 1
        if avg[7] > 0 and n[7] > 0:
            com = ditg.createCmd_2(dst=IP_DST,port="10008",tos=ditg.SERV_7,nPkts=str(n[7]),avg=str(avg[7]))
            print(com)
            os.popen(com)
            sum_out = sum_out + n[7]

        j = j+1
        i=i+1
        if i % ditg.SIZE==0 and i!=0:
            i=0
        print (i)
        print('Sum of Packets OUT: ' + str(sum_out))

        ##Wait next minute to avoid another detection
        check_time=False
        while check_time==False:
            now=datetime.datetime.now()
            try:
                if (now.minute== 4 or now.minute==17 or now.minute==31 or now.minute==41 or now.minute==54) and now.second==0:
                    now=ds1307.read_datetime()
                    str_time='"'+str(now.year)+'-'+str(now.month)+'-'+str(now.day)+' '+str(now.hour)+':'+str(now.minute)+':'+str(now.second)+'"'
                    os.system('sudo date --set '+str_time)
                    now=datetime.datetime.now()
                if now.minute%wait==1:
                    check_time=True
                else:
                    time.sleep(1)
            except:
                time.sleep(0.1)

        check_time=False
        while check_time==False:
            now=datetime.datetime.now()
```

```
            try:
                if (now.minute== 4 or now.minute==17 or now.minute==31 or now.minute==41 or now.minute==54) and now.second==0:
                    now=ds1307.read_datetime()
                    str_time='"'+str(now.year)+'-'+str(now.month)+'-'+str(now.day)+' '+str(now.hour)+':'+str(now.minute)+':'+str(now.second)+'"'
                    os.system('sudo date --set '+str_time)
                    now=datetime.datetime.now()
                if now.minute%wait==0:
                    check_time=True
                    print ("Time: "+str(now))
                    print ('Database Time: '+str(time_values[i]))
                else:
                    time.sleep(1)
            except:
                time.sleep(0.1)
        try:

            cmd = "pidof ITGRecv"
            PID = subprocess.check_output(cmd, shell=True).decode("utf-8")
            print ("pidof ITGRecv: "+str(PID))
            os.popen('sudo kill -9 '+str(PID))
            cmd = "pidof ITGSend"
            PID = subprocess.check_output(cmd, shell=True).decode("utf-8")
            print ("pidof ITGSend: "+str(PID))
            os.popen('sudo kill -9 '+str(PID))
        except:
            time.sleep(0.1)

def f2():
    while True:
        try:
            print("Start ITGRecv")
            os.popen('ITGRecv')
        except:
            time.sleep(1)
t1 = threading.Thread(target=f1, args=())
t2 = threading.Thread(target=f2, args=())

#Started the threads
t1.start()
time.sleep(4)
t2.start()

#Joined the threads
t1.join()
t2.join()
```

B.2 Start_ITGRecv.py

```
from subprocess import call
import threading
import subprocess
import random
import os
import time
import datetime
import json
import sys
import ditg

while True:
    try:
        print("Start ITGRecv")
        os.popen('ITGRecv')
    except:
        time.sleep(1)
```

B.3 ditg.py

```
#!/usr/bin/python

import pandas as pd
import time

# Constants
# Value of Interval Time in second
TIME = 300
TIME_MS = TIME * 1000
# Scale factor for the packet rate. It will be equal to [ pkts / scale ]
    per second.
SCALE = 400
# CSV Entries
SIZE = 576
# Simulation Time in CSV hours
SIM = 720
# Simulation in number of intevals
SIM_N = SIM * 12
computername="pi"
# CSV File
CSV = '/home/'+computername+'/Desktop/Hardware_Interface/CSV/
    vlan_interfaccial_DOS.csv'
# ToS
SERV_0 = "0"
SERV_1 = "32"
SERV_2 = "72"
SERV_3 = "96"
SERV_4 = "136"
SERV_5 = "160"
```

```
SERV_6 = "192"
SERV_7 = "224"

# IDT_OPT
# constant
c_idt = "-C"
#poisson
p_idt = "-O"
#esponential
e_idt ="-E"

# PS_OPT
# constant
c_ps = "-c"
# poisson
p_ps = "-o"
# esponential
e_ps ="-e"

# default value for protocol and packet size
DEFAULT_P = "UDP"
DEFAULT_PS = "512"

# Host Ip
dst = "169.254.207.100"

# Type of distribution
choice_i = c_idt
choice_s = c_ps


# Cmd creation
def createCmd(src, dst, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
     com = 'ITGManager ' + src + ' -a ' + dst + ' -b ' + tos + ' ' +
    choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t ' +
     str(TIME_MS-8000)
     return com

# Cmd creation
def createCmd_2(dst, port, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
     com = 'ITGSend -a ' + dst + ' -rp ' + str(port) + ' -b ' + tos + ' '
     + choice_i + ' ' + str(avg) + ' ' + choice_s + ' ' + ps_dim + ' -t
    ' + str(TIME_MS-10000)+ ' &'
     return com

# Cmd creation Iperf
def createCmd_3(dst, port, tos, nPkts, avg, protocol=DEFAULT_P, ps_dim=
    DEFAULT_PS):
     com = 'iperf3 -c ' + dst + ' -p ' + str(port) + ' -S ' + tos + ' ' +
     ' -k ' + str(nPkts) + ' &'
     return com
```

B.4 Set_Queue.py

```
from subprocess import call
import threading
import subprocess
import random
import os
import time
import datetime
import json
import sys
import ditg

from Controller_commands import *

max_rate_queue=100#Mbps
max_rate_queue=max_rate_queue*1000000
Default=str(max_rate_queue*20/100)#20%
Premium=str(max_rate_queue*80/100)#80%
Gold=str(max_rate_queue*100/100)#100%

def set_queue_eth2():
    NET = get_switchis()
    if NET != "NO NET" and NET!="[,]":
        i=1
        while i<NET.find("]"):
            mom_NET=NET[i:]
            datapath=NET[i:i+mom_NET.find(",")]
            i=i+mom_NET.find(",")+2
            port_id = switch_ports_name(datapath)
        time.sleep(0.2)
        i=1
        while i<NET.find("]"):
            mom_NET=NET[i:]
            datapath=NET[i:i+mom_NET.find(",")]
            i=i+mom_NET.find(",")+2
            port_id = switch_ports_name(datapath)
            ovsdb_addr(datapath)

            print(port_id)
            IP_Flag=True
            for index in range(0,len(port_id)):
                if port_id[index]=="eth2" or port_id[index]=="eth1":
                    print "Port_ID: "+port_id[index]
                    port = port_id[index][port_id[index].find("h")+1:]
                    if port_id[index]=="eth2":
                        set_queue(datapath, port_id[index], str(
    max_rate_queue), "{\"max_rate\": \""+Default+"\"}, {\"max_rate\": \"
    "+Premium+"\"}, {\"min_rate\": \""+Gold+"\"}")
                        IP_Destination="169.254.181.98"
                        set_Telecom_queue(datapath, port, IP_Flag,
    IP_Destination)

```

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

B.5 SendTime.py

```
#!/usr/bin/python
import serial
import time
import datetime
import os

os.popen("sudo chmod a+rw /dev/ttyACM0", 'w').write("Ao70pa45")


def read_all(port, chunk_size=200):
    """Read all characters on the serial port and return them."""
    if not port.timeout:
        raise TypeError('Port needs to have a timeout set!')

    read_buffer = b''

    while True:
        # Read in chunks. Each chunk will wait as long as specified by
        # timeout. Increase chunk_size to fail quicker
        byte_chunk = port.read(size=chunk_size)
        read_buffer += byte_chunk
        if not len(byte_chunk) == chunk_size:
            break

    return read_buffer

#'COM3'
ser = serial.Serial(
    port = '/dev/ttyACM0',
    baudrate = 115200,
    parity = serial.PARITY_NONE,
    stopbits = serial.STOPBITS_ONE,
    bytesize = serial.EIGHTBITS,
    timeout=0.5, # IMPORTANT, can be lower or higher
    inter_byte_timeout=0.1 # Alternative
    )
time.sleep(5)
flag = 0;
first_loop=0;
bufsize=0;
while True:
```

```
        ts = datetime.datetime.now();

        sec_mom=ts.second;
        minute_mom=ts.minute;
        hour_mom=ts.hour;
        DAY_mom=ts.day;
        MONTH_mom=ts.month;
        YEAR=str(ts.year);

        if sec_mom<10:
            sec='0'+str(ts.second);
        else:
            sec=str(ts.second);
        if minute_mom<10:
            minute='0'+str(ts.minute);
        else:
            minute=str(ts.minute);
        if hour_mom<10:
            hour='0'+str(ts.hour);
        else:
            hour=str(ts.hour);
        if DAY_mom<10:
            DAY='0'+str(ts.day);
        else:
            DAY=str(ts.day);
        if MONTH_mom<10:
            MONTH='0'+str(ts.month);
        else:
            MONTH=str(ts.month);

        DATA=YEAR+' '+MONTH+' '+DAY+' '+hour+' '+minute+' '+sec;

        if minute_mom%13==0 and sec_mom==0:
            flag=0;
        if flag==0:
      if first_loop==0:
                print("Time aligned at:")
                print(DATA)
                first_loop=1

            ser.write(DATA.encode()) #Send data to arduino. Activate
    arduino read pin and write to serial
            time.sleep(2)
            byteData = read_all(ser)
            if byteData.decode("utf-8")=="1":
                flag=1;
            else:
                print("ERROR--->resend data")
                flag=0;
            time.sleep(1)
        else:
            time.sleep(0.2)
```

B.6 ReadTime.ino

```
#include <Wire.h>
#include <TimeLib.h>
#include <DS1307RTC.h>

const char *monthName[12] = {
  "Jan", "Feb", "Mar", "Apr", "May", "Jun",
  "Jul", "Aug", "Sep", "Oct", "Nov", "Dec"
};

tmElements_t tm;

char inByte=0;
int lenbuffer=19;
byte bufferDATA[19];

String myString;
String Hour;
String Min;
String Sec;
String Day;
String Month;
String Year;

    void setup() {
      Serial.begin(115200);
      pinMode(LED_BUILTIN, OUTPUT);
      digitalWrite(LED_BUILTIN, LOW);
      while (!Serial) {
        ; // wait for serial port to connect. Needed for native USB
      }
    }

    void loop() {

      String DATA;
      if (Serial.available() > 0) //Waiting for request
      {
        Serial.readBytes(bufferDATA,lenbuffer);
        myString = String((char *)bufferDATA);
        Hour=myString.substring(11, 13);
        Min=myString.substring(14, 16);
```

```
        Sec=myString.substring(17, 19);
        Day=myString.substring(8, 10);
        Month=myString.substring(5, 7);
        Year=myString.substring(0, 4);

        tm.Hour = Hour.toInt();
        tm.Minute = Min.toInt();
        tm.Second = Sec.toInt();
        tm.Day = Day.toInt();
        tm.Month = Month.toInt();
        tm.Year = CalendarYrToTm(Year.toInt());
        RTC.write(tm);
        Serial.print("1");
        delay(1000);
      }

    }
```