A Study on Portable Load Balancer for Container Clusters

by

Kimitoshi Takahashi

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Committee

Kento Aida(Chair)	National Institute of Informatics / Sokendai
Atsuko Takefusa	National Institute of Informatics / Sokendai
Michihiro Koibuchi	National Institute of Informatics / Sokendai
Takashi Kurimoto	National Institute of Informatics / Sokendai
Shigetoshi Yokoyama	National Institute of Informatics / Gunma University

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Abstract

Today, most of the people in the world can not spend a day without using smartphones or PCs. They use these devices to access services provided by web applications on the Internet. These services include e-mail, social media, search engines, shopping site, etc., everything provided through the Internet. As these services become an indispensable part of the daily lives, portability of the application becomes very important.

For example, those who provide these services need to be able to recover from a disaster by migrating their web applications to different locations.

They also need to be able to expand their businesses to different countries, once the web service is successful in one country. It is also preferable for them to be able to migrate their services without a hassle at their convenience in order to avoid lock-ins.

For the portability of web applications, providing a web application consisting of a cluster of Linux containers is a promising candidate, since Linux containers can run on any Linux system regardless of the infrastructures. A container orchestrator (also called container cluster management system) is a tool to simplify the management of a cluster of containers that are launched on multiple servers. And it is expected to provide a uniform platform for container clusters by functioning as a middleware, which will improve the portability of web applications. However, none of the existing container orchestrators meets the expectation, because none of them has a standard way to set up the route for ingress traffic from the Internet automatically. Users need to set up a route for ingress traffic manually every time they start a new web application, depending on the type of the infrastructure. The lack of this standardized automation is one of the most critical problems that prevent container orchestrators from serving as a common middleware that facilitates the portability of web applications. Without solving this problem, the migration of a web application will never be easy, and will always require manual adjustment to the infrastructures.

In this dissertation, the author addresses this problem by proposing an architecture using a portable software load balancer that can run on any infrastructure. The author provides a cluster of software load balancers in containers that can be launched as a part of web applications for Kubernetes. The architecture is also capable of setting up the route for the ingress traffic automatically by using standard protocols. For this, Equal Cost Multi Path(ECMP) routes are populated through Border Gateway Protocol(BGP) in order to provide redundancy and scalability at the same time.

By using the proposed architecture, web application clusters no longer depend on the load balancers provided by infrastructures. And hence, container orchestrators become being able to better serve as a common middleware.

The author has implemented a containerized software load balancer using Linux kernel's IPVS, and carried out experiments with the following criteria: 1) verify if the proposed load balancer works correctly both in the cloud and the on-premise datacenter. 2) verify if the proposed load balancer has a sufficient performance level for 1 Gbps and 10 Gbps networks. 3) verify if the proposed redundancy architecture using ECMP with BGP properly functions.

From the results of the experiment, it has been shown that the proposed load balancers can run in an on-premise data center, Google Cloud Platform (GCP), and Amazon Web Service (AWS). Therefore the proposed load balancers can be said to be portable.

In the case of 1 Gbps network environment, the throughput of the IPVS in a container with Layer 3 Direct Server Return(L3DSR) setting has been about 1.5 times higher than that of existing iptables DNAT rules, which is prepared by Kubernetes's daemons as an internal load balancer. And it has been shown that the

proposed load balancer has more than enough throughput to fill up 1 Gbps bandwidth. In the case of 10 Gbps network environment, while a single IPVS load balancer in the container can provide only 1/4 of required throughput, ECMP setups using more than four of them can deal with 10 Gbps equivalent of the traffic. Therefore, the proposed load balancer has been proven to be portable with sufficient performance in both 1 Gbps and 10 Gbps network environments.

The author has also verified that ECMP routes are properly created on the upstream router, upon launch of new load balancer containers. The update of the ECMP routing table was correct and quick enough, i.e., within 10 seconds, throughout 20 hours experiment. The maximum performance level of a cluster of load balancers has scaled linearly up to four times as the number of the load balancer containers has been increased up to four. The maximum aggregated throughput obtained through the experiment is 780k [req/sec], which is limited by the CPU performance of the benchmark client and can be improved using better hardware in the future experiment. Therefore the author has proved that proposed load balancer has the capability of the automatic setup of ingress traffic in a redundant and scalable manner.

Sooner or later, the day when the network in a data center becomes all 100 Gbps will come. Therefore, it is essential to improve the performance of the portable load balancers in future work. The author has started to implement a novel software load balancer using eXpress Data Path(XDP) technology. The preliminary result, where the maximum throughput is about 390K [req/sec] with single-core packet processing, indicates that this technology is very promising. The author estimates that about five of the software load balancer using this technology with 16 core packet processing can provide enough throughput in 100 Gbps environments in the future.

The proposed load balancer has been verified to be portable while providing sufficient throughput in 10 Gbps environment.

And the proposed redundancy architecture using ECMP with BGP has also been verified to function properly. As a consequence, the proposed architecture with this load balancer will help improve the portability of web applications.

The outcome of this study will benefit users who want to improve the portability of web applications and deploy them anywhere they want. Moreover, the result of this study will potentially benefit users who want to use a group of different cloud providers and on-premise data centers across the globe seamlessly. In other words, users will become being able to deploy a complex web service on aggregated computing resources on the earth, as if they were starting a single process on a single computer.

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Chapter 1

Introduction

1.1 Motivation

1.1.1 Web application

Today, a great number of the people in the world can not spend a day without using smartphones or personal computers (PCs) to retrieve information from the Internet for work or for daily life. For example, people use these devices to look up web pages, emails, social media and sometimes to play games. These services are often called web applications or web services, where information is delivered using Hyper Text Transfer Protocols (HTTP) or Hypertext Transfer Protocol Secure (HTTPS) from servers at the other end of the Internet. Web applications are provided by various organizations, including commercial companies, government, non-profitable organizations, etc.

For example, Google provides a variety of web services including, Gmail, Search engines, Google Suite, etc. Facebook provides social media service, Amazon provides shopping sites. Governments provides information regarding the service they provide to their citizens. Schools often provide a syllabus to their students, which is important for campus life. The author calls those organizations that provide web applications, web application providers hereafter.

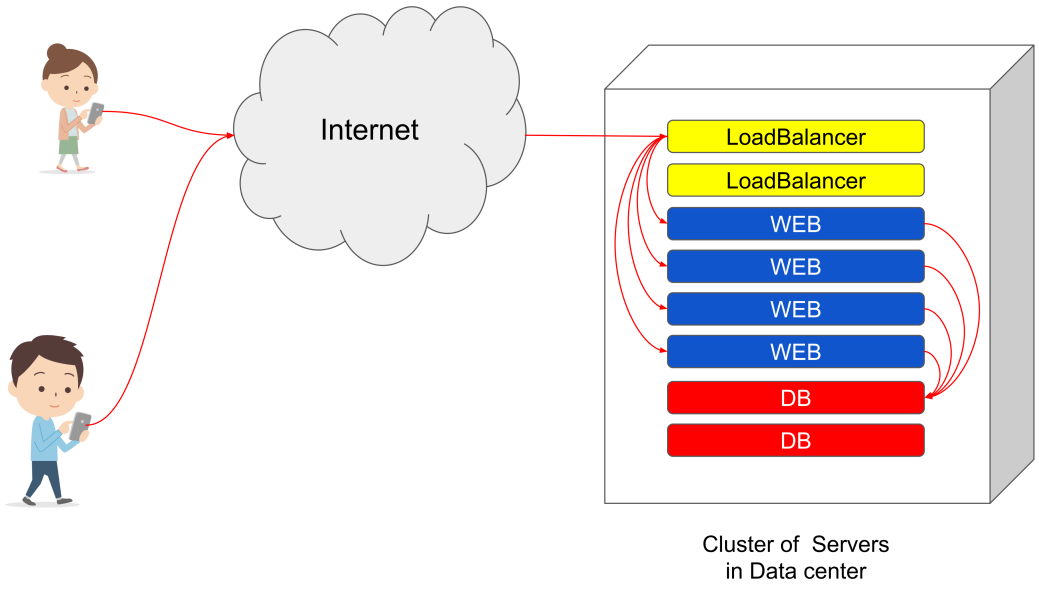


Figure 1.1: An example of web application cluster.
The load balancers distribute requests from clients to multiple web servers. The web servers form responses using data retrieved from the database servers and send it back to the clients. Sometimes the web servers also store and update important data into the database servers.

A client program on PCs or smartphone sends out requests to servers, and the servers respond with data that is requested using HTTP or HTTPS. Servers for web applications are usually computers located in a data center. In the data center multiple servers cooperate to fulfill the need of the clients. A group of these servers

is often called a web application cluster or a web cluster. Figure 1.1 shows schematic diagram of an example of a web application cluster.

In this example, there are two load balancers, four web servers and two database (DB) servers that work together to respond to requests from the clients. The load balancers distribute the requests from the clients to multiple web servers. Then the web servers form responses using data retrieved from the database servers and send it back to the clients. Sometimes the web servers also store and update important data into the database servers.

1.1.2 Portability of web application

As web applications become an essential part of daily life, improving their portabilities[1] is getting to be very important [1, 2]. If a web application is portable, it will become much easier for web application providers to migrate the service when there is a disaster, or when they want to expand their business to different geographical locations, etc.

Nowadays, an outage of the web application service will cause a critical problem. If something happens to a web application cluster in a data center, people will not be able to access the necessary information. For example, if web pages run by local government stops, people will not be able to access the information regarding public services. If a shopping site run by a company stops, customers can no longer buy products and the revenue of the company will be greatly decreased. Outages of web applications by giant companies can have an even bigger impact. An outage of Gmail or Google search engine will probably stop most of the business activities around the world. Service down of Amazon.com affect buyers and many businesses that sell products on its platform.

In order to prevent such outages, preparing another web application cluster in a different location in the case for disasters is very important. For that purpose, it is desirable if a web application cluster can be easily migrated to a different data center. Migration of a web application cluster becomes more realistic by making the web application itself portable with the use of Linux container technology, which is explained later.

Improving the portability of a web application cluster also has another benefit. If an e-commerce service is successful in Japan, the company that runs the service might want to start the same service in other countries, for example, in Europe. In this situation, the company probably wants to start the same web application cluster somewhere in Europe, because, for European customers, responses from a web site in Europe is quicker than those from a web site in Japan. If the web application cluster is portable, starting the service in a different country will be very easy.

Improving the portability of a web application cluster is also very important for other purposes, including cost performance optimizations, meeting legal compliance, and avoiding vendor lock-in problems. These are the main concerns for web application providers in e-commerce, gaming, financial technology (Fintech) and Internet of Things (IoT) field.

The purpose of this research is to improve the portability of web applications by proposing a common architecture, where web application providers can easily deploy their services across the world, regardless of cloud providers or data centers they use.

1.1.3 Ideal infrastructure for portable web application

In order to improve the portability of web applications, standardizing infrastructure will be important. An ideal infrastructure probably have the following features; 1) having common middleware to manage web

[1] The author defines portability as the extent of easiness when making a web application interoperable in various infrastructures.

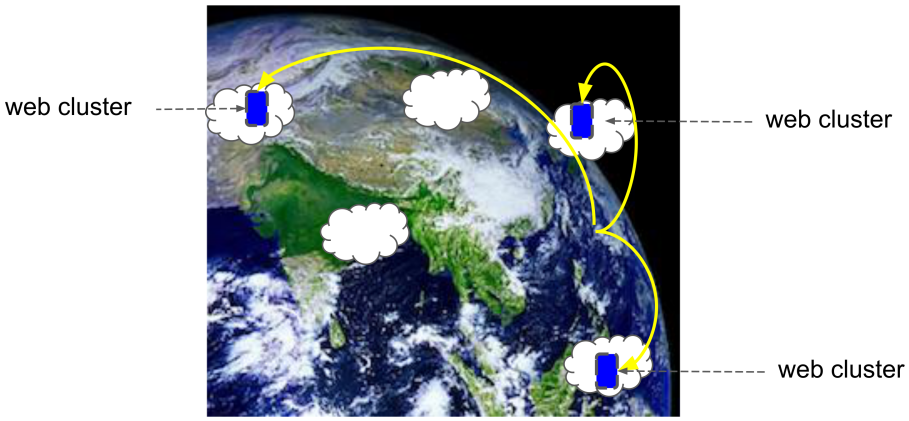


Figure 1.2: Migration of web application cluster to different locations.
It is desirable to be able to migrate a web cluster from one place to another with the easiness of on push button.

application clusters, 2) capable of storing data in globally consistent data storage, 3) capable of routing global traffic based on proximity to the client. Figure1.3 shows an exemplified global container infrastructure having these features. Container orchestrators, as a common middleware, launch and manage web applications consisting of container clusters. Important data are stored in globally consistent data storage, which is similar to the Google spanner [3, 4] or CockroachDB [5]. The traffic is routed to the closest data center using anycast [6, 7].

Each of these features is important, and research efforts are on-going in many institutions. In this study, the author focuses on the research regarding container orchestrator as a common middleware. By realizing global container infrastructure portability of web application will be significantly improved, and web application providers will be able to deploy their web applications whenever and wherever they want. Also, they will be able to move their web applications quickly depending on a variety of circumstances, including disaster recovery, cost performance optimization, and compliance to government regulations due to trade wars, etc.

1.2 Infrastructure for web applications

1.2.1 On-premise data center

Historically, most of the web application providers purchased servers and installed them in server housing facilities called data centers. In this type of infrastructure, web application providers typically need to sign a contract with data center company for server housing rack spaces, buy servers and install them in their rented racks by themselves. They also install OS and software stacks needed to run their web applications in the servers. Since web application providers place servers in their facilities (either owned or rented) by themselves, and they are responsible for managing the servers, this type of infrastructure is often called on-premise infrastructure in contrast to Cloud Computing infrastructure.

Preparing data centers, installing the servers and configuring software stacks for web application services often require a considerable amount of time, money and effort. If web application providers want to expand their services to different countries or if they want to prepare for natural disasters by preparing an additional web application cluster in a different data center, they probably need about the same amount of time, money and effort required to build their original infrastructures. Therefore migration of web application in this type

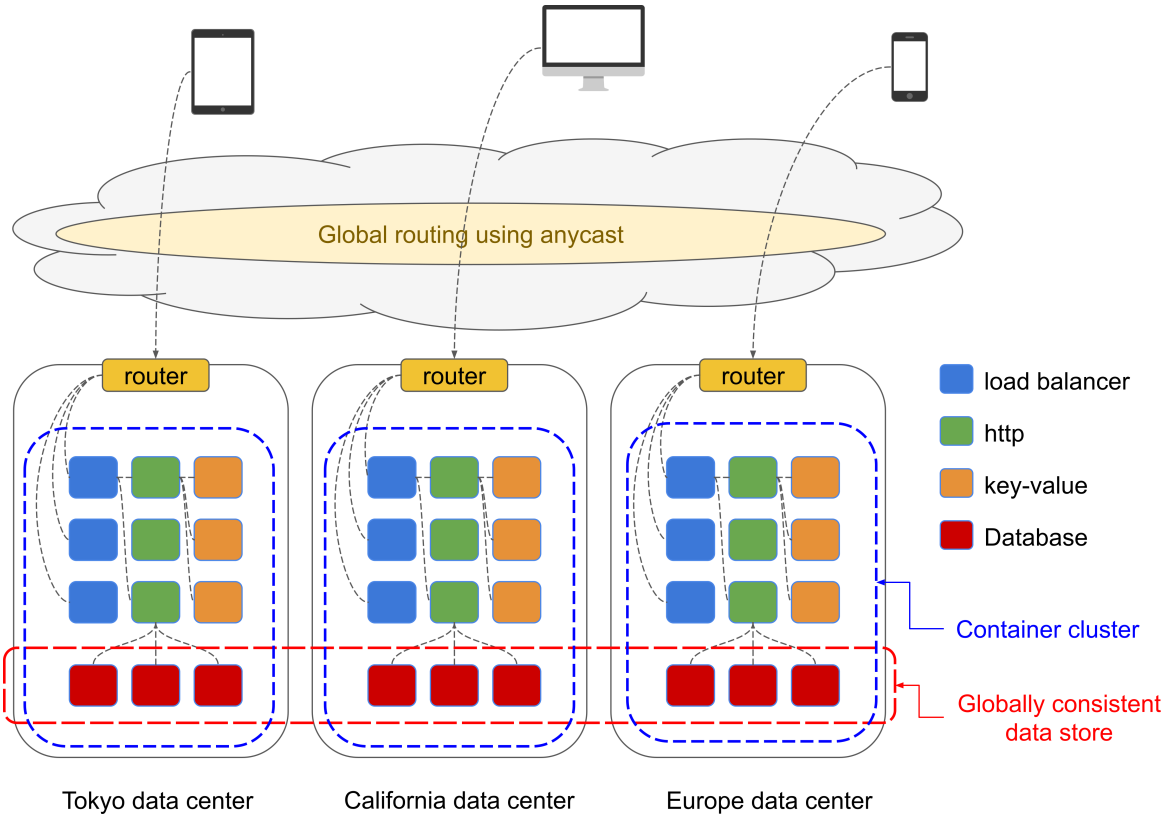


Figure 1.3: An ideal global container infrastructure.
Multiple web application clusters, each of which consisting of a cluster of containers, are deployed in three different data centers as an example. In each of the data center, container orchestrator manages the container cluster. Important data are stored in a globally consistent data store. Access from the client is routed to the closest data center using anycast.

of infrastructures has always been a daunting task.

1.2.2 Cloud computing

The emergence of Cloud Computing made many things easier for web application providers than before. Cloud computing utilizes a virtual machine (VM) technology, e.g. KVM, Xen, or VMware. Cloud computing service providers offer VMs to web application providers with pay-per-use billings.

Citations for KVM, Xen, and VMware

Figure 1.4 compares different type of usages of a single physical server and Figure 1.4 (b) shows an example architecture of VM technology. VMs share a single physical server. A full OS including Linux kernel is running on top of the virtual machine represented by the hypervisor. Each VM behaves almost as same as a single physical server. Since VMs are fractions of a single physical server, server resources are utilized with finer granularities. Web application providers can start their services with a cluster of VMs, which is smaller than a cluster of physical servers, and hence resulting in lower cost.

Cloud providers generally prepare physical servers and OSs for VMs before renting it to users, and they also provide an easy to use web user interfaces. As a result, users only need to click a few buttons on web browsers and wait for a few minutes before obtaining up-and-running VMs. This simplicity will bring agility to web application providers when they launch their services. And since computing resources are offered with per-second pay-per-use billings, web application providers can quickly reduce the cost by stopping excessive VMs, when the demand for computing power is scarce. This was impossible when web application providers

purchased physical servers and used them as bare metal servers. In short, cloud computing brought users agility, flexibility, and cost-effectiveness.

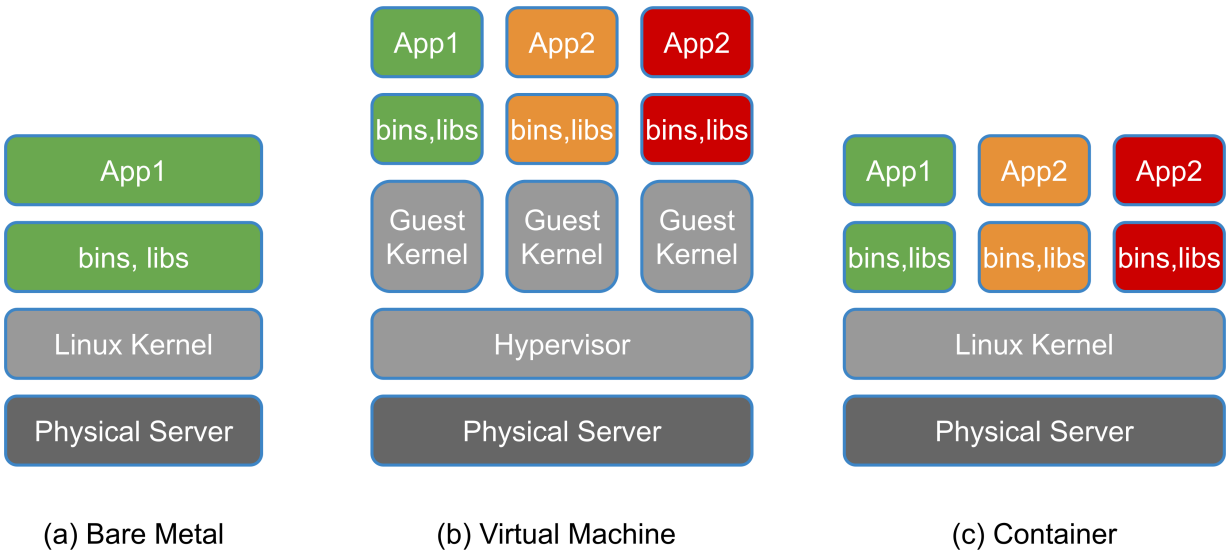


Figure 1.4: Bare Metal, Virtual Machine and Container technology The difference in physical server usage between (a) Bare Metal servers, (b) Virtual Machine and (c) Container technology. (a) Bare Metal servers is a word to describe conventional physical servers in contrast to Virtual Machines. On top of a Bare Metal server, an operating system and application programs are running. (b) Virtual Machine technology utilizes physical server hardware and a hypervisor. The hypervisor provides generic representations of server hardware, which are called virtual machines. A full operating system and applications are running on each of the virtual machines. (c) Container technology separates applications by containing them to their respective namespaces. Applications can not see each other's file systems, networks, users and process IDs unless they belong to the same namespace. Since container technology merely relies on Linux kernel's namespace function and optionally cgroup, a containerized process does not have any additional overhead compared with a process running on a conventional physical server and operating system. Container technology can be also utilized on top of virtual machines.

1.2.3 Container technology

More recently, Linux containers [8] have come to draw a significant amount of attention. Figure 1.4 (c) shows an example architecture of container technology. Linux containers are merely the processes with separate execution environments that are created using the Linux kernel's namespace feature. The namespace feature can isolate visibility of resources on a single Linux server.

Every process in a container is assigned to a certain namespace, and if two processes belong to different namespaces, they can not see each other's resources. Linux kernel implements filesystem namespace, PID namespace, network namespace, user namespace, IPC namespace, and hostname namespace. For example, every filesystem namespace can have its own root filesystem, and every network namespace can have its own network devices and IP addresses. Therefore, it is possible to configure processes as if they were running in different Linux systems by assigning them to different namespaces, although they share kernel and hardware. While a VM needs to run a full OS on top of a hypervisor and hence imposes extra overhead, a process in Linux container is merely a process with a dedicated namespace and hence expected to impose much less extra overhead [9].

The Linux container can run on any Linux systems including physical servers and VMs. Due to the widespread usage of Linux systems, the Linux container can run in most of the cloud infrastructures and on-premise data centers, which is beneficial for migrations.

Several management tools are available for Linux containers, including LXC [10], systemd-nspawn [11] and Docker [12]. These tools assign an appropriate namespace to a process upon the launch and make it look like running in its own virtual Linux system. For example, container tools restore a file system from an archive file every time a container is launched. Container tools also set up separate network interfaces with separate IP addresses in the container's namespace.

The fact that each container has its own file system that is restored from a single archive file brings a significant benefit, i.e. a program binary and shared libraries are always exactly the same regardless of the base infrastructure. Therefore a process in a container is guaranteed to behave exactly the same manner, even if totally different data centers or cloud providers are used. This was not easy when there was no container technology. Because there are many flavors of Linux distributions, and even if the same distribution is used, there was always a chance that a slight difference in a program binary version or library versions would break the expected behavior.

In addition to that, containers can have own version of libraries in their respective filesystems, in other words, libraries in any container can be independently updated without influencing other containers and host OSs. In conventional technologies, processes on a single server are dependent on common shared libraries, and hence updates of the library sometimes have caused unexpected side effects to those programs that depend on that library. Container tools alleviate these problems by packing necessary libraries into archives.

Thanks to these benefits, container technologies are very attractive for improving the portability of the web applications and hence, facilitating their migrations. Considerable efforts in utilizing container technologies for web applications are ongoing. And to simplify the deployment of a complex web application that consists of interdependent container clusters, several container orchestrators (container cluster management systems)[2] have been in development.

1.2.4 Container Orchestrator

While container tools focused on launching individual container, a container orchestrator is a tool to simplify the management of a cluster of containers that are launched on multiple servers. Figure 1.5 shows the important features for the container orchestrator for web applications; 1) **Configuration file:** Orchestrator should manage container clusters based on a configuration file. The configuration file must be able to describe container cluster internals and relationships between interdependent container clusters. 2) **Scheduling:** Depending on the configuration file, the orchestrator must be able to pick servers and launch containers on them. Orchestrator must also maintain the state described in configuration files, for example, the orchestrator may need to maintain the number of running containers. 3) **Ingress routing:** The orchestrator must be able to set up routes for incoming traffic from the Internet to multiple containers in a redundant and scalable manner. 4) **Internal routing:** If the web application consists of multiple interdependent container clusters, the orchestrator must be able to set up routes between them in a redundant and scalable manner.

In a configuration file a user can describe how a container cluster should be configured, and also can describe relationships between different container clusters. As a result, a user can launch a web application that consists of interdependent container clusters just by supplying the configuration file to the orchestrator. For example, a web application cluster in Figure 1.5 consists of three different functionalities, namely http

[2]The author uses the word 'container orchestrator' and 'container cluster management system' for the same meaning and uses them interchangeably

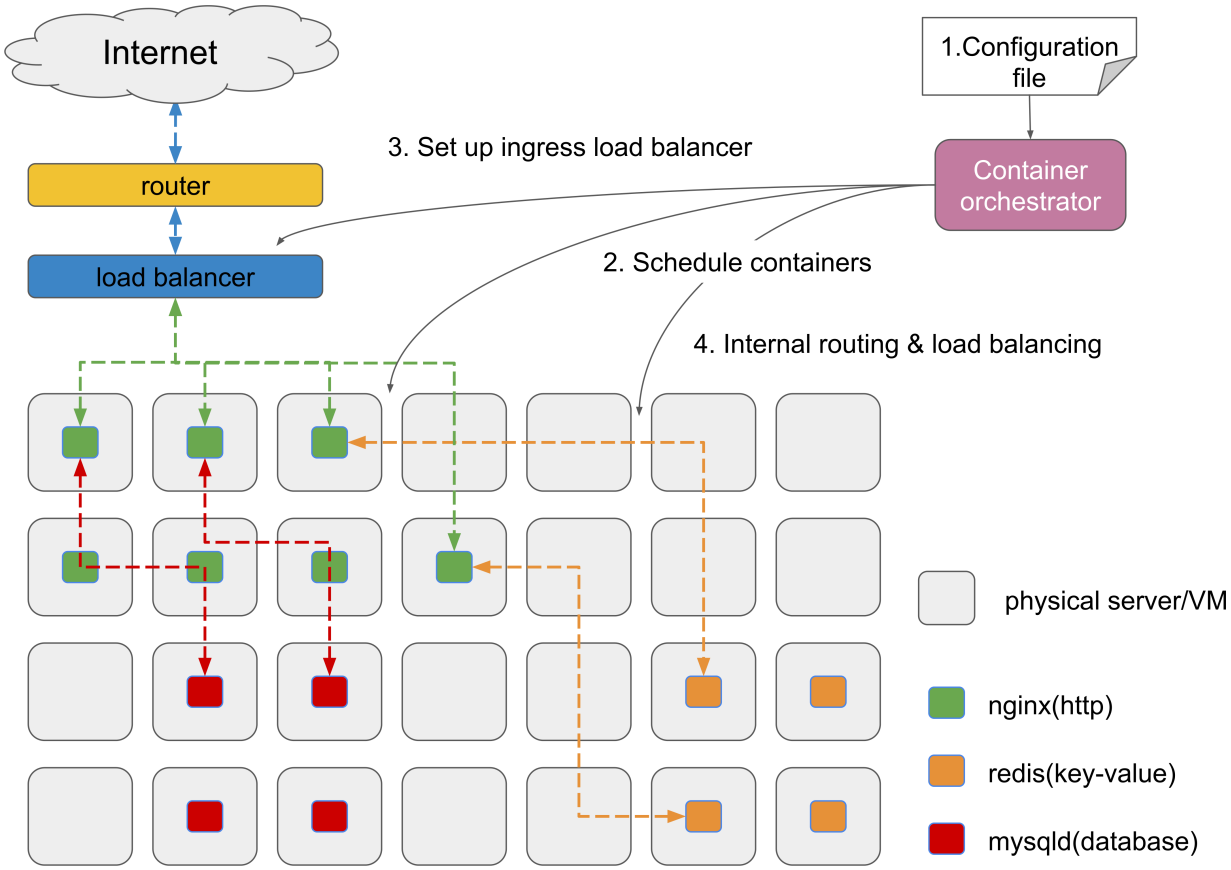


Figure 1.5: A web application cluster and container orchestrator. A web application cluster consists of nginx (http), redis (key-value store) and mysqld (database) is depicted in this figure. Each of the component consists of a container cluster. Container orchestrator receive configuration file(1), schedule containers(2), set up ingress routing using load balancer(3) and set up internal routing(4).

server, key-value store, and database. Each of those consists of a container cluster. In the configuration file, the relationships between the http server cluster, the key-value store cluster, and the database cluster should be specified. The configuration file must also contain how each cluster should be configured, including the number of the containers and resources assigned to them. If these requirements are met for the configuration file, users only need to feed the configuration file to the orchestrator to launch this web application.

Thanks to these features, an orchestrator can be viewed as if it is an Operating System for a server farm in a data center, which not only schedules and launches containers on the server farm but also routes the traffic to the appropriate containers. By using orchestrators, a user can start a complex web application that consists of multiple interdependent container clusters, on multiple servers in a data center, as easily as starting a single process on a single computer. As a result, web applications become portable, and a user can also easily migrate their web applications at his or her convenience. And migrated web applications are guaranteed to behave exactly the same manner, not only because the same program binary and libraries are used in container, but also because container orchestrators hide differences among the base infrastructures.

Several container orchestrators are available, including Kubernetes, Docker swarm and Mesos/Marathon. Each of the container orchestrators varies in target applications, and thus has the strength and weaknesses.

Kubernetes Kubernetes [13] is an open source container orchestrator, originally developed at Google based on their experiences of production container orchestrator, Borg [14]. Since Google runs a lot of large scale

web applications, Kubernetes are considered to be best suited to run web applications.

Docker swarm Docker Swarm is a container orchestrator built in Docker daemon itself. Users can execute regular Docker commands, which are then executed by a swarm manager. The swarm manager is responsible for controlling the deployment and the life cycle of containers.

Mesos/Marathon Mesos [15] is a common resource sharing layer for different type of applications like Hadoop, MPI jobs, and Spark in a Data Center. By using Mesos user does not need to have dedicated physical server cluster for each applications. Marathon is a framework which uses Mesos in order to orchestrate Docker containers. Because of the broader scope of applications, an out of box Mesos might not be particularly suited for web applications.

	Kubernetes	Docker Swarm	Mesos Marathon
Config file	YAML	YAML	JSON
Scheduling	Yes	Yes	Yes
Ingress routing	Manual* Cloud load balancer**	Manual*	Manual*
Internal routing	iptables DNAT	IPVS	haproxy

*Users are expected to set up a static route to one of the internal load balancers manually.
**Support for Cloud load balancer is only available in limited infrastructures including GCP, AWS, Azure and OpenStack.

Table 1.1: Container orchestrator comparison. Important aspects of features as web application infrastructures are compared.

Table1.1 compares these orchestrators based on necessary features as an infrastructure for web applications. Although all of these orchestrators mostly satisfy the requirements, they fail to support the automatic routing of the ingress traffic from the Internet. Docker swarm and Mesos/Marathon rely on manual set up of a static routing for ingress traffic. Only Kubernetes has the functionality to manage cloud load balancer so that ingress traffic is automatically routed to containers in a redundant and scalable manner. However, this functionality is applicable only for a few cloud environments.

To the best knowledge of the author, none of the existing container orchestrators fully supports features that automatically set up ingress routing in a redundant and scalable manner. The author believes solving this problem is an open and important topic for research and development, and therefore intends to pursue it.

1.2.5 Kubernetes architecture and problem

As is mentioned in the previous subsection, none of the existing container orchestrators provides full support for automatic set up of ingress traffic routing. In the case of Kubernetes, the problem is its partial support for external load balancers. Here the author elaborates on the situation.

Figure 1.6 shows an exemplified Kubernetes cluster. A Kubernetes cluster typically consists of a master and nodes. They can be physical servers or VMs. On the master, daemons that control the Kubernetes cluster are typically deployed. These daemons include, apiserver, scheduler, controller-manager and etcd. On the nodes, kubelet and proxy are deployed. The kubelet daemon will run *pods*, depending on the PodSpec (pod specification) information obtained from the apiserver on the master. A *pod* is a group of containers that share the same network namespace and cgroup, and is the basic execution unit in a Kubernetes cluster. The proxy daemon on every node will set up iptables Destination Network Address Translation (DNAT) rules that function as the internal load balancer.

Thanks to the expressive syntax of the configuration file, Kubernetes allows users to easily launch complex web applications that consist of multiple interdependent container clusters as if they were launching a single application program. It also allows users to modify the state of their container clusters, just by feeding the modified configuration file. Kubernetes always tries to make the states of containers to match its desired state that is written in the configuration file.

When a service is created, the master schedules where to run *pods*, and the kubelets on the nodes launch them accordingly. At the same time, the master sends out requests to cloud provider's API endpoints, asking them to set up external cloud load balancers that distribute ingress traffic to every node in the Kubernetes cluster. The proxy daemon on the nodes also setup iptables DNAT rules. The ingress traffic will then be evenly distributed by the cloud load balancer to all of the existing nodes, after which it will be distributed again by the DNAT rules on the nodes to the designated *pods*. The returning packets follows the exact same route as the incoming ones.

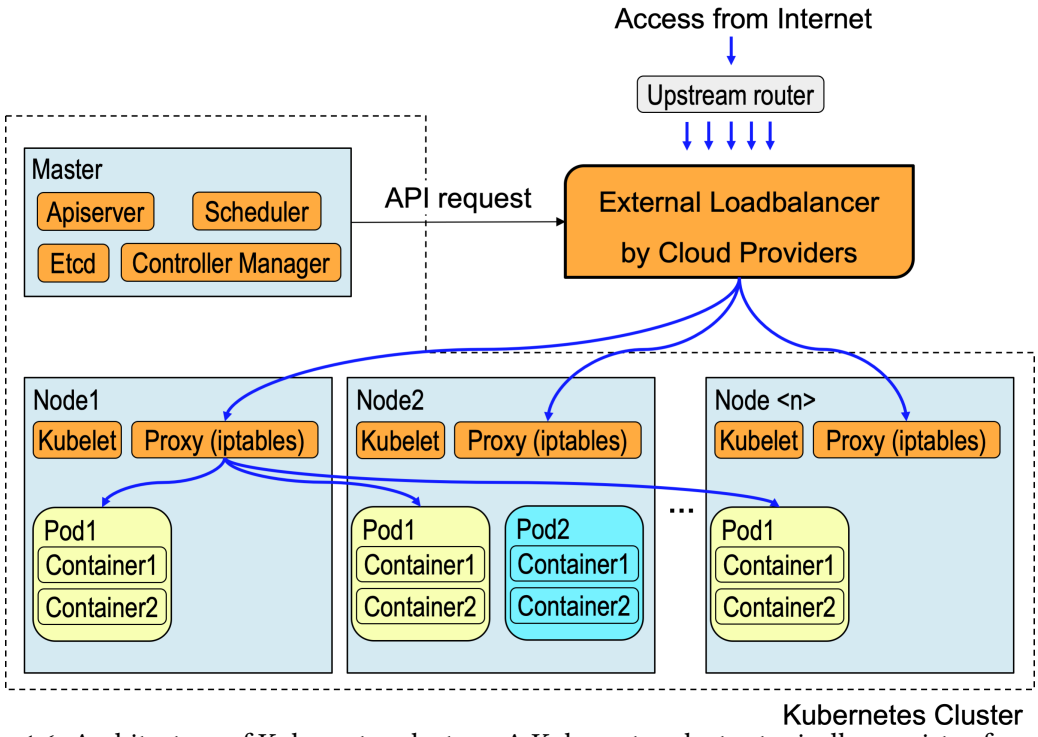


Figure 1.6: Architecture of Kubernetes clusters. A Kubernetes cluster typically consists of a master and nodes, which can be physical servers or VMs. On the master, daemons that control the Kubernetes cluster are typically deployed. On the nodes, daemons that control container and the internal routing are typically deployed. Kubernetes depends on external load balancer to route ingress traffic from the internet into the container cluster. However, it seems impractical to support all of the existing load balancers.

In general, load balancers are often used to distribute high volume traffic from the Internet to hundreds of web servers. They are implemented as a dedicated hardware or as a software on commodity hardware. Major cloud providers have developed software load balancers [16, 17] dedicated for their infrastructures. For on-premise data centers, there are a variety of proprietary hardware load balancers.

Kubernetes utilizes load balancers to route ingress traffic into the Kubernetes cluster in a redundant and scalable manner. Software load balancers for cloud infrastructure have APIs, through which Kubernetes can control the behavior. However, most of the proprietary hardware load balancers for on-premise data center do not have such APIs.

In environments where there are supported load balancers, namely cloud environments including Google

Cloud Platform (GCP), Amazon Web Applications (AWS), or OpenStack, Kubernetes can automatically set up the route for the ingress traffic upon the launch of a web application. The cloud load balancers will distribute ingress traffic to every node (physical servers or VMs) that might host containers. Once the traffic reaches the nodes, Kubernetes nicely route them to appropriate containers using iptables DNAT based internal load balancer. However, in environments where there are no supported load balancers, Kubernetes fails to automatically set up the route for ingress traffic. In such cases Kubernetes expects users to manually set up a route for the ingress traffic, which generally lacks redundancy and scalabilities. In this way, Kubernetes fails to provide a uniform interface to container clusters, which degrades the portabilities of web applications.

Other container orchestrators, e.g. Docker swarm or Mesos/Marathon, do not even have partial support for load balancers and expect users to manually set up the route for ingress traffic. Therefore this is a generic problem that current container cluster orchestrators possess.

1.3 Focus of the dissertation

1.3.1 The purpose

The ultimate goal of this research is to improve the portability of web applications by providing global container infrastructure. Doing so will give users the freedom to migrate their services when there is a disaster, expand their businesses, and prevent vendor lock-ins, etc. To bring this into reality, container orchestrators need to function as a common middleware. Container orchestrators must provide the same interfaces to web applications, regardless of the base infrastructure, e.g., cloud providers or on-premise data centers. However, existing orchestrators fail to do so, since the way to route the ingress traffic from the Internet is either by setting up a static route or by relying on cloud load balancers.

The purpose of this research is to propose a generic architecture that can set up a route for ingress traffic automatically without relying on the cloud load balancers. For that purpose, the author proposes a cluster of software load balancer containers, instead of relying on load balancers provided by infrastructures.

Proposed load balancer can run both in cloud infrastructures and in on-premise data centers and can be utilized to set up the route for ingress traffic automatically. The proposed load balancer should possess the following features; 1) The proposed load balancer properly functions both in on-premise data centers and cloud infrastructures. 2) The proposed load balancer has redundancy and scalability. 3) The proposed load balancer can set up routes for ingress traffic automatically. 4) The proposed load balancer can update the load balancing table appropriately.

Figure 1.7 shows schematic diagram of an example architecture for such load balancers. A web application that consists of nginx, redis, and mysqld, each being a cluster of containers, is running in the server farm. There is also a cluster of software load balancer containers, which is also a part of the web application cluster, running in the same server farm. All of the containers are deployed and managed by the container orchestrator. The orchestrator also communicates with the upstream router using Border Gateway Protocol (BGP) [18], so that the ingress traffic from the Internet is forwarded to the existing load balancer containers in a redundant and scalable manner by using Equal Cost Multi Path (ECMP) [19] routing table.

Container orchestrators are good at managing a cluster of containers. They can keep the number of containers at the desired level. And also they can scale the number of containers depending on the amount of traffic. Therefore it seems to be very reasonable to make container orchestrator also manage load balancer containers. With the help of ECMP routing table on upstream router, redundancy and scalability are accomplished simultaneously. Since BGP and ECMP are the standard protocol supported by most of the commercial router hardware, the author regards this architecture is preferable in most of the environments.

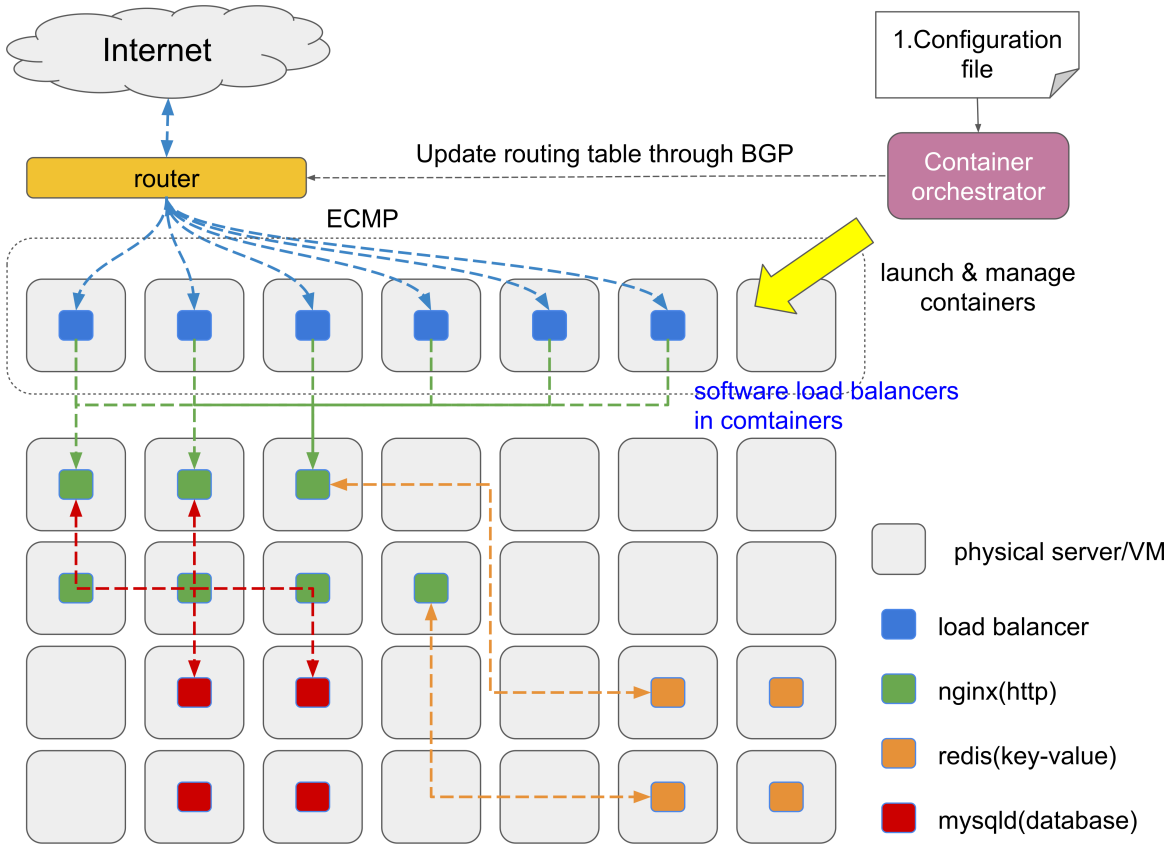


Figure 1.7: Load balancer for container clusters.
In order distribute the traffic, container orchestrator launches a cluster of software load balancer containers. The container orchestrator also communicates with the upstream router through BGP protocol and the router set up an ECMP routing rule in the routing table.

1.3.2 The method

The author implements the proposed software load balancer that works well with Kubernetes, as a test case, since Kubernetes seems most appropriate for web application clusters at the moment. The implemented load balancer uses the following technologies; 1) To make the load balancer runnable in any environment, Linux kernel's Internet Protocol Virtual Server (IPVS) [20] is containerized using Docker [12]. 2) Container orchestrator manages the load balancer containers, and the ingress traffic follows the ECMP routing tables on the upstream router. These will make the load balancer redundant and scalable. 3) To set up the ECMP route automatically, the author makes the load balancer containers advertise route through BGP protocol. 4) To make the load balancer capable of updating the load balancing table appropriately, the author makes the load balancer acquire information about web server containers from the orchestrator.

While the method to acquire information about running containers is specific to the orchestrator, i.e, Kubernetes, the other technologies used are not. Therefore, the author expects that the load balancer with the same architecture can also be implemented for the other container orchestrators, i.e., Docker Swarm and Mesos/Marathon, just by writing the code to acquire information about running containers.

The author verifies the feasibility of the proposed load balancer through experiments, with the following criteria; 1) Portability: whether the load balancer can run in both on-premise data centers and cloud infrastructures. 2) Redundancy and scalability: whether the throughput is improved by increasing the number of load balancers. 3) Performance: whether the load balancer has sufficient throughput for 1 Gbps and 10 Gbps network.

The author also explores the possibility of enhancing the performance of the proposed load balancer, for the faster network than 10 Gbps. The author implements the novel load balancer using eXpress Data Path (XDP) technology [21] for that purpose and shows preliminary experimental results.

1.3.3 Contribution

Contributions of this thesis can be summarized as follows: 1) The author proposes a cluster of software load balancer containers that is deployed as a part of web applications. By removing the dependencies on external load balancers provided by infrastructures, users can deploy their web applications in the same manner regardless of the infrastructure, which will improve the portability of web applications. 2) The author implements a proof of concept system using Open Source Software (OSS), which means that anyone can test drive the proposed load balancers and use them in production for free. 3) The author carries out a performance evaluation and quantitably prove the feasibility of the proposed load balancer up to 10 Gbps network environment. 4) The author points out the remaining problems for future improvement and explores other technology to be used in faster networks.

The outcome of this study will improve the portability of web applications, and potentially benefit users who want to use a group of different cloud providers and on-premise data centers across the globe seamlessly. In other words, users will become being able to deploy a complex web application on aggregated computing resources on the earth, as if they were starting a single process on a single computer.

1.4 Outline

Refine outline

The rest of the paper is organized as follows;

This chapter provides explanations of the following technologies; 1) Overlay network 2) Multicore packet processing 3) IPVS load balancer 4) XDP technology. These are the underlying technologies used in this study, and knowledge of these is necessary to understand the contents of this thesis.

Chapter 3 provides discussion of load balancer architecture suitable for container clusters. One of the most important problems of existing container orchestrators is that none of them has full support for automatically setting up routes for ingress traffic in a redundant and scalable manner. In order to solve this problem, the author proposes a cluster of software load balancer in containers, which is deployed as a part of the web application clusters. This chapter provides a discussion of such load balancer architecture. The author also presents an implementation of the proof of the concept system for the proposed load balancer architecture in detail.

Chapter 4 presents the results of the evaluation.

The author verifies the feasibility of the proposed load balancer through experiments, with the following criteria; 1) Portability: whether the load balancer can run in both on-premise data centers and cloud infrastructures. 2) Redundancy and scalability: whether the throughput is changed by changing the number of load balancers. 3) Performance: whether the load balancer has sufficient throughput for 1 Gbps network.

In the previous chapter, the author evaluated the feasibility of the proposed load balancer in 1Gbps network. In Chapter 5, the author shows that the proposed load balancer has sufficient throughput in 10Gbps network. The author also discusses how to improve the performance levels in faster networks, e.g., 100 Gbps and finds that there are rooms for improvements in both the container network and the software load balancer itself. Although these should be explored further in the future work, the author presents preliminary experimental results of a novel software load balancer using eXpress Data Plane (XDP) technology.

Chapter 6 presents related work of this study.

The author presents related work regarding the following subjects: (1) Portability of web applications. (2) Software load balancers for Kubernetes. (3) Cloud load balancers. (5) Load balancer tools in the container context.

Chapter 7 presents conclusion of this study.

Chapter 2

Background

This chapter provides explanations of the following technologies; 1) Overlay network 2) Multicore packet processing 3) IPVS load balancer 4) XDP technology. These are the underlying technologies used in this study, and knowledge of these is necessary to understand the contents of this thesis.

Overlay networks are used to deploy Kubernetes clusters in most cases in order to separate the node network and container network. The author has also found that the choice of the operation mode of the overlay bnetwork greatly affects the throughput of the load balancers, as will be explained in Chapter 4. Therefore, flannel, which is one of the overlay networks and is used in this study, is explained in detail.

Secondly, the author explains how to utilize multi-core CPUs for packet processing in Linux. The Linux kernel comes with built-in features for multi-core packet processing. However, the default setting of Linux distribution might not be necessarily optimized for the best performance, which sometimes hinders the understanding of experimental results. That was the case when the author first carried out the experiment, and therefore the author explains about it.

Thirdly, the author explains Linux kernel's IPVS load balancer, because IPVS is used to implement the proposed load balancer in this study. The IPVS has three operation modes, and two of them used in this study are also explained.

Lastly, the author briefly explains about novel XDP technology. The author plans to replace IPVS based load balancer with the one based on XDP technology in future work. The author has already started the implementation of such load balancer and presents a preliminary result in Chapter 5. The explanation of XDP technology is necessary to understand why it is supposed to be faster than IPVS.

2.1 Overlay network

An overlay network is used to deploy a Kubernetes cluster in most cases in order to separate the node network and container network. In the case of Kubernetes, every *pod*[1] is assigned with its own IP address. If the administrator of Kubernetes cluster plans to host up to 10 *pod*s on a single node, roughly 10 times larger IP address space is required for container network than for node network. And if one plans to host up to 100 *pod*s on a single node, 100 times larger IP address space is needed. Therefore in practice, it is often convenient to separate administrations of node network and container network using overlay network.

2.1.1 Container network

There are several types of container network including, veth [22], MACVLAN [23], IPVLAN [24], host network. There are good reviews of these network in [25, 26, 27]. The author uses the container network that uses bridge and veth because of the popularity and easiness of the setups. Here the setup used in the experiments is explained.

Figure 2.1 shows a schematic diagram of the container network used in this study. The veth kernel module creates a pair of network interfaces that act like a pipe. One of the peer interfaces is kept in the host network

[1] A *pod* is a group of containers that share the same network namespace and cgroup, and is the basic execution unit in a Kubernetes cluster.

namespace and the other is added to the container namespace. The interface in the host network namespace is connected to a network bridge, docker0. In the case of Docker, most of the veth setup is done by the Docker daemon.

The communication between two containers on the same physical node is through the docker0. The communication with the outside of the node further follows the routing rules in the kernel, and optionally translated using iptables Masquerade or Source Network Address Translation (SNAT) [28].

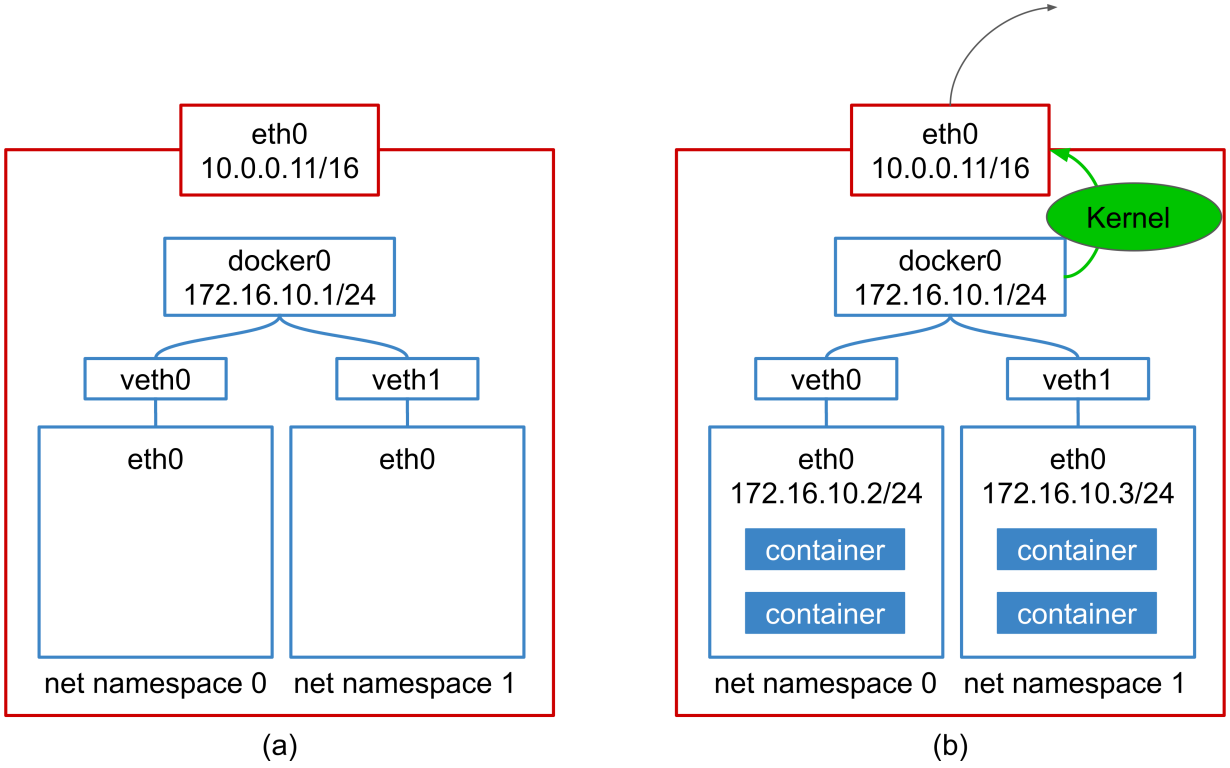


Figure 2.1: Docker networks setup. (a) Two pairs of network interefaces (veth0,eth0) and (veth1,eth0) are created. Each of the pairs acts like a pipe. The veth0 and veth1 are placed in the host (node) network namespace, and connected to the docker0 bridge. The eth0s are placed in respective container namespaces. (b) Communication between network namespace 1 and 2 is through the docker0. Communication with the outside of the node follows the routing table inside the kernel.

When a container needs to communicate with other containers on different nodes, the kernel needs to know on which node the peer container exists. The kernel normally does not know this, but if there is the help of overlay network [29], the kernel eventually finds out the next hop towards peer container.

2.1.2 Overlay Network

There are several choices for the overlay networks with popular ones being flannel [30], calico [31], weave [32], etc. The author used flannel throughout this study because of its popularity and easiness. Flannel has three types of backend, *i.e.*, operating modes, host-gw, vxlan, and udp [33]. These are explained here.

host-gw mode

In the host-gw mode, the flanneld installed on a node simply configures the routing table in the kernel based on the IP address assignment information of the overlay network, which is stored in the etcd [34] on the master node of Kubernetes. When *pod1* on the node1 sends out an IP packet to *pod2* on the different node,

node2, the node1 consults its routing table and learn that the IP packet to *pod2* should be sent out to the node2. Then, the node1 forms Ethernet frames containing the destination MAC address of the node2 without changing the IP header, and send them out. Since packets are not encapsulated in the host-gw mode, the MTU size remains 1500 bytes.

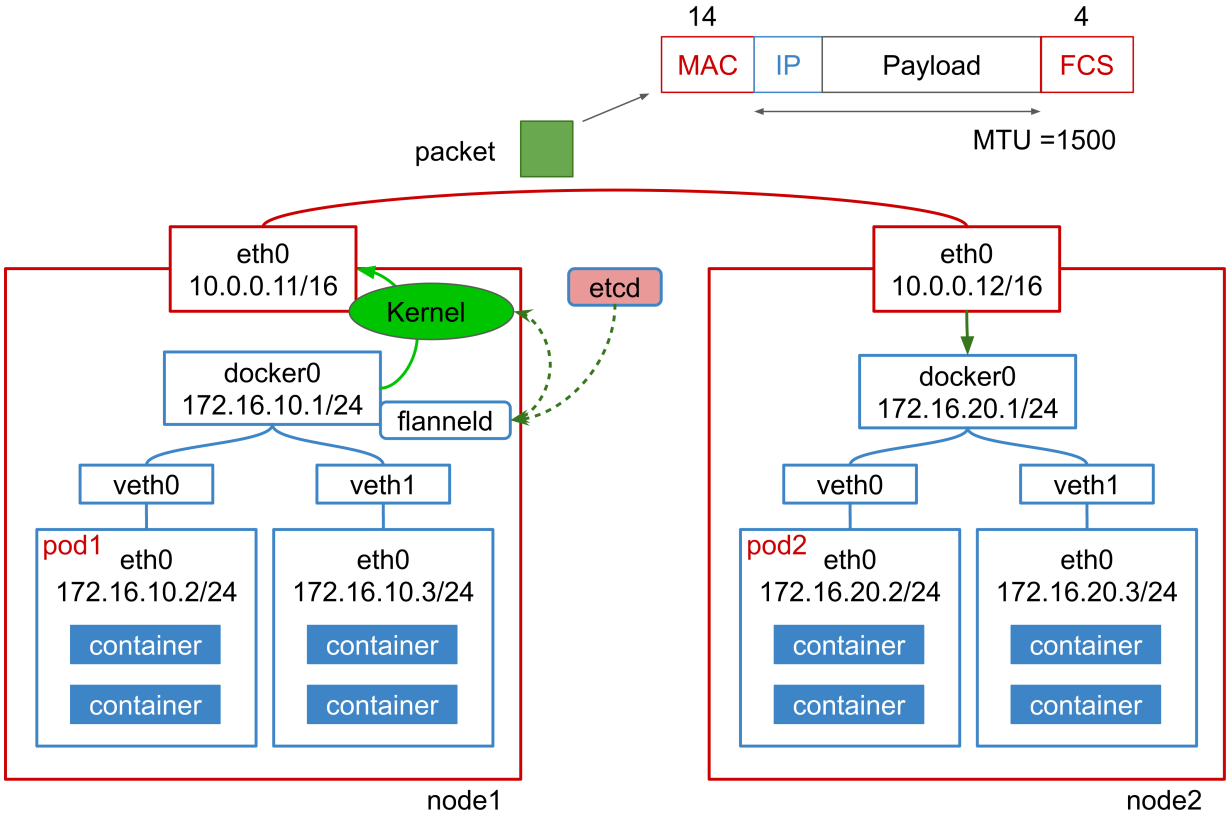


Figure 2.2: Flannel setup with host-gw mode. The *pod1* on the node1 sends out an IP packet to *pod2* on the node2. After receiving packets from the *pod1*, the node1 learns that *pod2* is on the node2, and forward the packets to the node2 without any encapsulation. The flanneld continuously updates routing entries for containers in the routing table on each node.

vxlan mode

In the case of the vxlan mode, flanneld creates the Linux kernel's vxlan device, flannel.1. Flanneld will also configure the routing table appropriately based on the information stored in the etcd. When *pods* on different nodes need to communicate, the packet is routed to flannel.1. The vxlan functionality of the Linux kernel identify the MAC address of flannel.1 device on the destination node with the help of flanneld, then form an Ethernet frame toward that MAC address. The vxlan then encapsulates the Ethernet frame in a UDP/IP packet with a vxlan header, after which the IP packet is eventually sent out. An additional 50 bytes of header is used in the vxlan mode, thereby resulting in an MTU size of 1450 bytes.

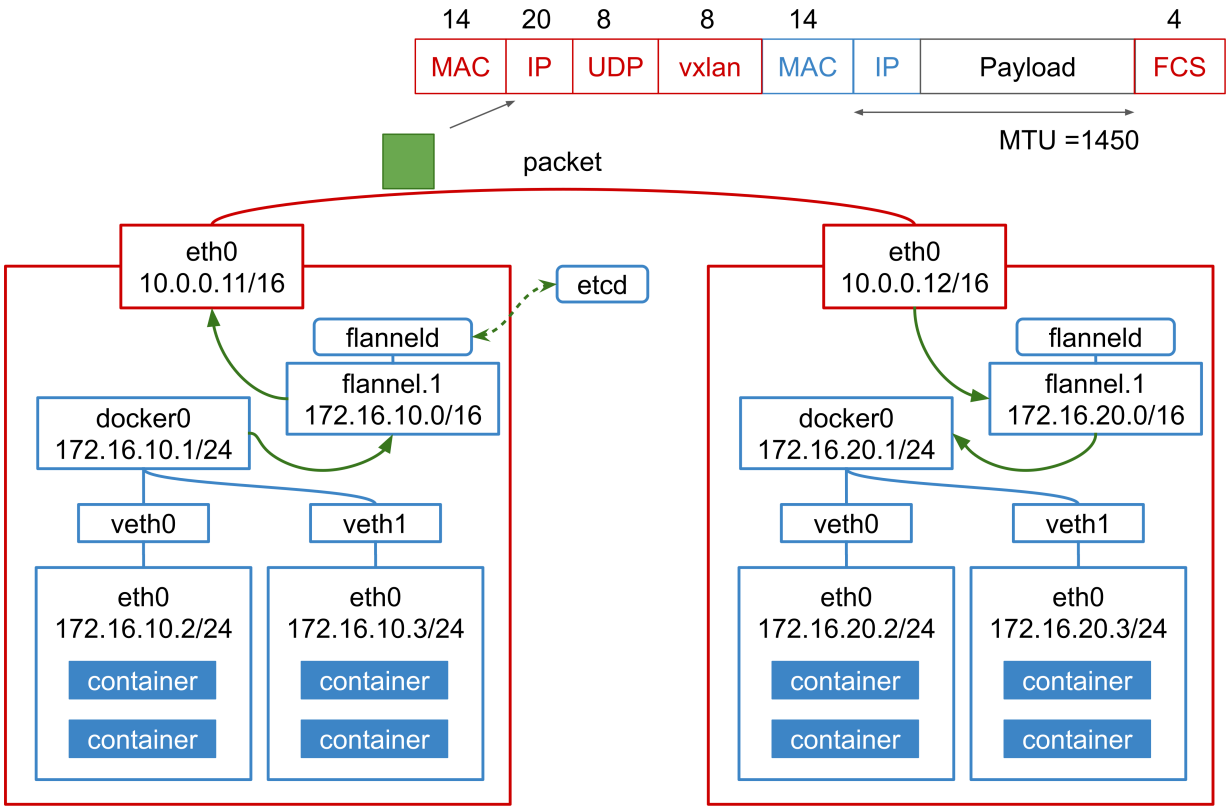


Figure 2.3: Flannel setup with vxlan. The flanneld on the nodes updates routing entries for containers. In addition to that, the flanneld also create Linux kernel's vxlan device, flannel.1 on every node. When packets are sent out through flannel.1 devices, the flannel.1 encapsulate the original packets with vxlan headers.

udp mode

In the case of udp mode, flanneld creates the tun device, flannel0, and configures the routing table appropriately based on the information stored in the etcd. The flannel0 device is connected to the flanneld daemon itself. An IP packet routed to flannel0 is encapsulated by flanneld, and eventually sent out to the appropriate node. The encapsulation is done for IP packets. In the case of the udp mode, only 28 bytes of header are used for encapsulation, which results in an MTU size of 1472 bytes.

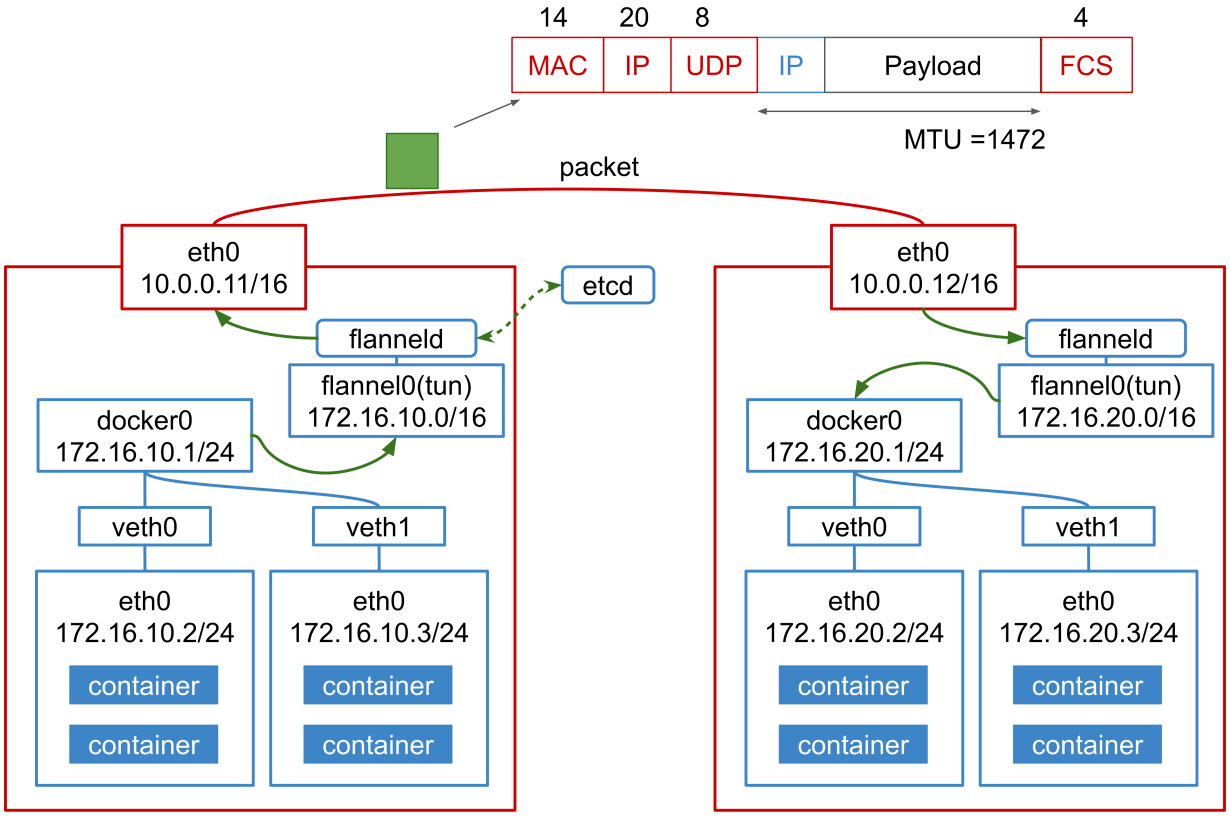


Figure 2.4: Flannel setup with udp. The flanneld creates the tun device, flannel0, and updates routing entries for containers. The flannel0 device is connected to the flanneld daemon itself. When packets are sent out through flannel0 devices, the flanneld daemon encapsulates the original packets with udp headers.

2.1.3 Caveats of the overlay network

There are caveats in using overlay network. The author explains two of them that are identified in the course of this study.

The first is that overlay network without encapsulation has issues when used in cloud environments. There are chances when there is a gateway host without a knowledge of the overlay network between two containers. When such gateway host receives a packet destined to a container without encapsulation, it simply drops the packet because it does not know where to send it.

The second is that there is an issue when two containers communicate with a host without knowledge of the ovelay network. Since the packets are translated using SNAT, the host can not identify if the two connections are coming from a single container or from two containers only by looking into IP and TCP headers.

Overlay network and cloud

Although the host-gw mode is expected to be most efficient since no packet encapsulation is used, it has a significant drawback that prohibit it to work correctly in cloud platforms. The host-gw mode simply sends out a packet without encapsulation. If there is a cloud gateway between nodes, the gateway cannot identify the proper destination, therefore it drops the packet.

The author conducted an investigation to determine which of the flannel backend mode would be usable on AWS, GCP, and on-premise data centers. The results are summarized in Table 2.1. In the case of GCP,

mode	On-premise	GCP	AWS
host-gw	OK	NG	NG
vxlan	OK	OK	OK
udp	OK	OK	OK

Table 2.1: Flannel backend modes. The host-gw mode without encapsulation does not work in GCP nor in AWS.

an IP address with the prefix length of 32 (/32 in CIDR notation) is assigned to every VM host and every communication between VMs goes through GCP's gateway. As for AWS, the VMs within the same subnet communicate directly, while the VMs in different subnets communicate via the AWS's gateway. Since the gateways do not have knowledge of the flannel overlay network, they drop the packets; thereby, they prohibit the use of the flannel host-gw mode in those cloud providers.

Communication with router

The overlay network also causes a problem when communicating with the host that has no knowledge of the overlay network. Fig. 2.5 shows schematic diagram of network architecture of a container cluster system. There is a node network (physical server network) with the IP address range of 10.0.0.0/16 and an overlay network with the IP address range of 172.16.0.0/16. The node network is the network for nodes to communicate with each other. The overlay network is the network setups for containers to communicate with each other. An overlay network typically consists of appropriate routing tables on nodes, and optionally of tunneling setup using IPIP [35] or vxlan [29]. The upstream router usually belongs to the node network. When a container in the Fig. 2.5 communicates with any of the nodes, it can use its IP address in 172.16.0.0/16 range as a source IP, since every node has proper routing table for the overlay network. However, when a container communicates with the upstream router that does not have routing information regarding the overlay network, the source IP address must be translated by SNAT rules on the node where the container resides.

The SNAT caused a problem when the author tried to co-host multiple load balancer pods for different services on a single node and let them connect the upstream router directly. This was due to the fact that the BGP agent used in our experiment only used the source IP address of the connection to distinguish the BGP peer. The agent on the router behaved as though different BGP connections from different containers belonged to a single BGP session because the source IP addresses were identical due to the SNAT.

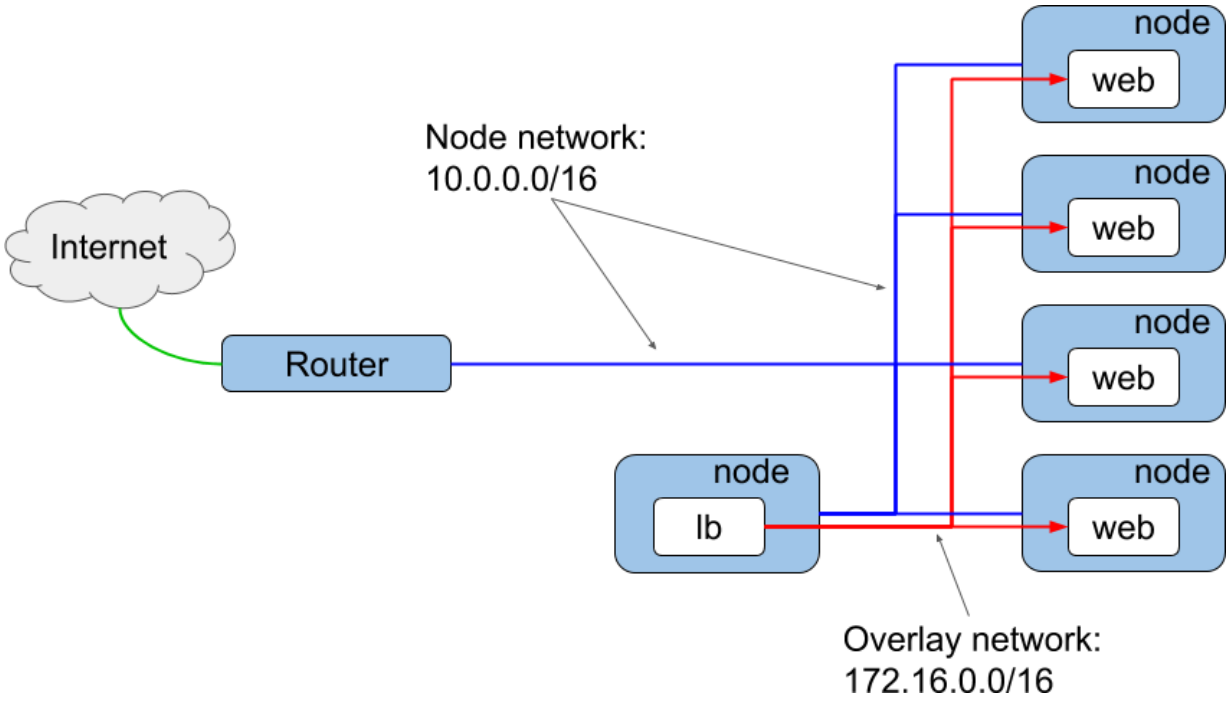


Figure 2.5: A network architecture of container cluster system. A load balancer (lb) pod (the white box with "lb") and web pods are running on nodes (the blue boxes). The traffic from the internet are forwarded to the lb pod by the upstream router using the node network, and the distributed to web pods using the overlay network.

2.2 Multicore packet processing

The Linux kernel comes with built-in features for multi-core packet processing. However, the default setting of Linux distribution might not be necessarily optimized for the best performance, which sometimes hinders the understanding of experimental results. That was the case when the author first carried out the experiment, and therefore the author explains about it.

The performance of a computer system has been improved significantly thanks to the development of multi-core CPUs. One of the top of the line server processors from Intel now includes up to 28 cores in a single CPU. In order to enjoy the benefits of multi-core CPUs in communication performance, it is necessary to distribute the handling of interrupts from the NIC and the subsequent IP protocol processing to the available physical cores.

Receive Side Scaling (RSS) [36] is a technology to distribute handling of the interrupt from NIC queues to multiple CPU cores. Receive Packet Steering (RPS) [36] distributes the IP protocol processing to multiple CPU cores by issuing inter core software interrupts.

Since performance levels of a load balancer could be affected by these technologies, the author conducted an experiment to determine how performance levels of the load balancers are changed by the RSS and RPS settings in Chapter 4. The lest of this section explains how RSS and RPS are enabled and disabled in the experiment. The NIC used in the experiment is Broadcom BCM5720, which has four rx-queues and one tx-queue. Figure 2.6 shows the interrupt request (IRQ) number assignments to those NIC queues at the time of experiments.

```
81: eth0-tx-0
82: eth0-rx-1
83: eth0-rx-2
84: eth0-rx-3
85: eth0-rx-4
```

Figure 2.6: The IRQ numbers assigned for each RX/TX queue, which is obtained from "/proc/interrupts". IRQ numbers from 81 to 85 are assigned to different tx and rx queues.

RSS

When packets arrive, they are distributed to these rx-queues depending on the flow each packet belongs to. Each receive queue has a separate IRQ associated with it. The NIC triggers this to notify a CPU when new packets arrive on the given queue. Then, the notified CPU handles the interrupt, and performs the protocol processing. According to the [36], the CPU cores allowed to be notified is controlled by setting a hexadecimal value corresponding to the bit maps indicating the allowed CPU cores in "/proc/irq/[IRQ number]/smp_affinity". For example, in order to route the interrupt for eth0-rx-1 to CPU0, one should set "/proc/irq/82/smp_affinity" to binary number `0001`, which is 1 in hexadecimal value. Furthermore, in order to route the interrupt for eth0-rx-2 to CPU1, one should set "/proc/irq/83/smp_affinity" to binary number `0010`, which is 2 in hexadecimal value.

In this dissertation, the setting that distributes interrupts from four rx-queues separately to CPU0, CPU1, CPU2, and CPU3 is referred to as "RSS = on". It is configured as the setting in Figure 2.7(a). On the other hand, "RSS = off" means that all the interrupts from any rx-queue are routed to CPU0. It is configured as the setting in Figure 2.7(b).

```
echo 1 > /proc/irq/82/smp_affinity
echo 2 > /proc/irq/83/smp_affinity
echo 4 > /proc/irq/84/smp_affinity
echo 8 > /proc/irq/85/smp_affinity
```

((a)) **RSS=on**

```
echo 1 > /proc/irq/82/smp_affinity
echo 1 > /proc/irq/83/smp_affinity
echo 1 > /proc/irq/84/smp_affinity
echo 1 > /proc/irq/85/smp_affinity
```

((b)) **RSS=off**

Figure 2.7: RSS settings used in this study. (a) This setting distributes interrupts from the IRQ# 82–85 to CPU0–CPU3, respectively. (b) This setting directs all the interrupts from IRQ# 82–85 to CPU0.

RPS

After the interrupts from the NIC are handled, IP protocol processings are carried out. The RPS distributes IP protocol processing by placing the packet on the desired CPU's backlog queue and wakes up the CPU using inter-processor interrupts. The author has used the settings in Figure 2.8(a) to enable the RPS.

Since the hexadecimal value "fefe" represented as "1111 1110 1111 1110" in binary, this setting will

```
echo fefe > /sys/class/net/eth0/queues/rx-0/RPS_cpus
echo fefe > /sys/class/net/eth0/queues/rx-1/RPS_cpus
echo fefe > /sys/class/net/eth0/queues/rx-2/RPS_cpus
echo fefe > /sys/class/net/eth0/queues/rx-3/RPS_cpus
```

((a)) **RPS=on**

```
echo 0 > /sys/class/net/eth0/queues/rx-0/RPS_cpus
echo 0 > /sys/class/net/eth0/queues/rx-1/RPS_cpus
echo 0 > /sys/class/net/eth0/queues/rx-2/RPS_cpus
echo 0 > /sys/class/net/eth0/queues/rx-3/RPS_cpus
```

((b)) **RPS=off**

Figure 2.8: RPS settings used in this study. (a) IP protocol proccessings are distributed to CPU1–CPU7 and CPU9–CPU15. (b) Distribution of IP protocol proccessings is prohibitted. Original CPUs that recieved interrupts will process the IP protocols.

distribute protocol processing to all of the CPUs, except for CPU0 and CPU8. The CPU0 and CPU8 are logically different but share the same physical core[2]. In this dissertation, the author refers to this setting as "RPS = on". On the other hand, "RPS = off" means that no CPU is allowed for RPS. In this case, the IP protocol processing is performed on the CPUs the initial hardware interrupt is received. It is configured as the settings in Figure 2.8(b).

The RPS is especially effective when the NIC does not have multiple receive queues or when the number of queues is much smaller than the number of CPU cores. That was the case in the experiment. Since there were only four rx-queues, RSS could utilize only four physical cores out of eight. Figure 2.9 shows a schematic diagram of the settings used in this study. While merely enabling RSS results in four core packet processing, enabling RPS results in eight physical core packet processing.

[2]The hardware used in the experiment had Hyper-Threading functionality [37], therefore each of the physical cores are shared by two logical cores.

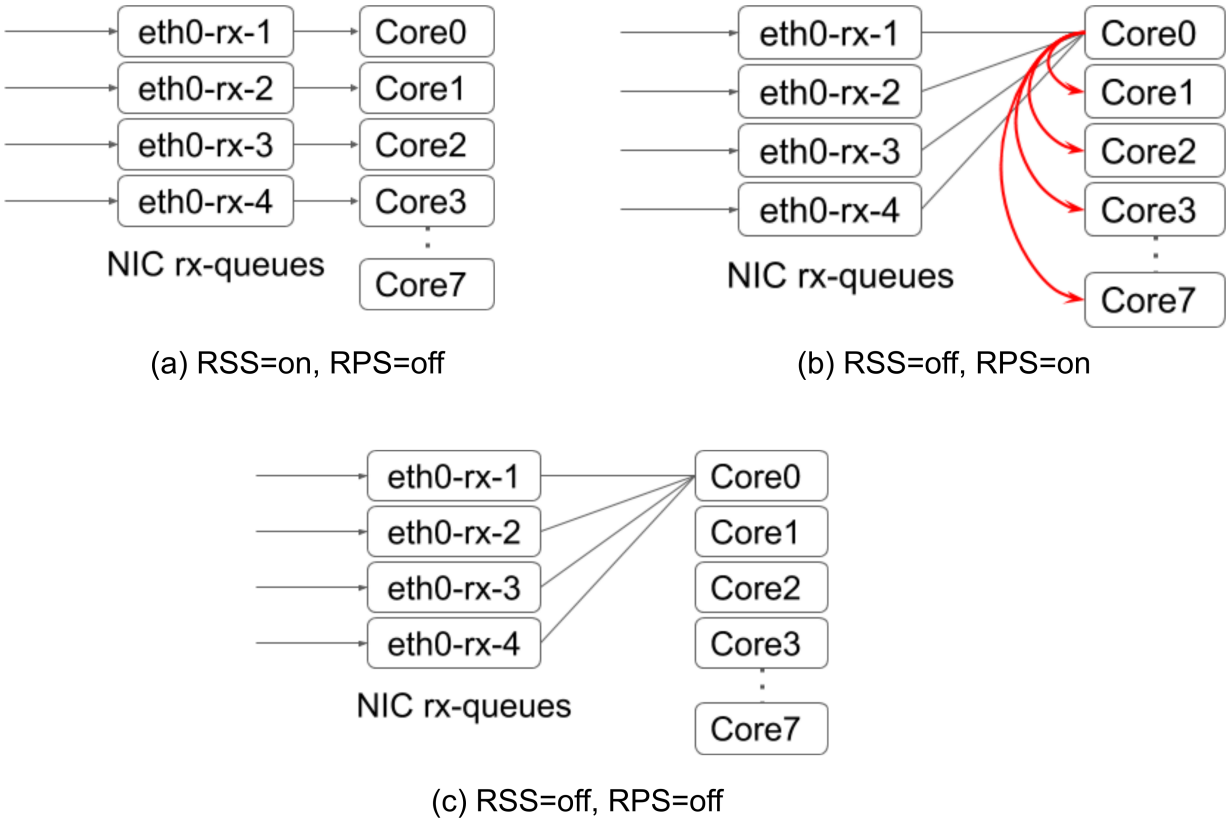


Figure 2.9: RSS/RPS settings used in this study. (a) In the case of "RSS=on,RPS=off", only four cores are used for packet processing. (b) In the case of "RSS=off,RPS=on", eight cores are used for packet processing. (c) In the case of "RSS=off,RPS=off", only one core is used for packet processing.

2.3 IPVS load balancer

The IPVS is a Layer-4 load balancer capability, which is included in the Linux kernel 2.6.0 released in 2003 or later, to distribute incoming Transmission Control Protocol (TCP) traffic and User Datagram Protoco (UDP) traffic to *real servers*[3] [20]. For example, IPVS distributes incoming Hypertext Transfer Protocol (HTTP) traffic destined for a single destination IP address, to multiple HTTP servers running on multiple nodes in order to improve the performance of web services. The destination IP address is often called Virtual IP (VIP) because the VIP and the multiple HTTP servers form a virtual service. The IPVS has three operation modes, Network Address Translation (NAT), Tunneling and (Direct Return) DR. In this study the author used NAT mode and Tunneling mode. Here the author explains these two modes briefly[4].

2.3.1 NAT mode

Figure 2.10 shows a schematic diagram of NAT mode of IPVS. The NAT mode works as follows: When a user accesses a virtual service provided by the server cluster, a request packet destined for a VIP arrives at the load balancer. The load balancer examines the packet's destination address and port number, if they match a virtual service in the load balancing table, one of the real servers are selected depending on the scheduling algorithm, and the information regarding the connection is added into the connection hash table. Then, the destination IP address and the port number of the original packet are translated to those of the real server, and the

[3]The term, *real server* refers to worker servers that will respond to incoming traffic, in the original literature [20]. The author will also use this term in the similar way.

[4]Readers interested in the DR mode, are referred to the original literature [20].

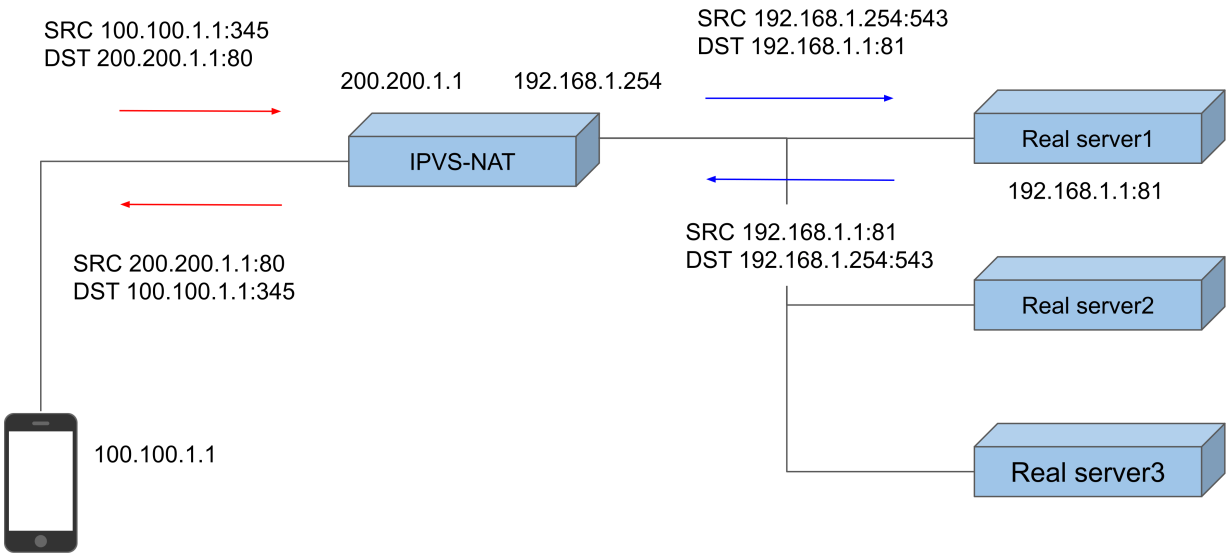


Figure 2.10: Schematic diagram of IPVS NAT mode. The IP packets arriving at the IPVS NAT enabled host are forwarded to real servers. The IP headers are translated by IPVS NAT function in the Linux kernel.

packet is forwarded to the real server. When an incoming packet belongs to an established connection, the connection can be found in the hash table and the packet is rewritten and forwarded to the right server. When response packets arrive, the load balancer rewrites the source address and port number of the packets to those of the virtual service, and send them back to the clients. When a connection terminates or timeouts, the corresponding entry is removed from the connection hash table. In this dissertation, the author refers to this NAT mode simply as IPVS hereafter.

2.3.2 Tunneling mode

Figure 2.11 shows a schematic diagram of the tunneling mode of IPVS. IPIP tunneling (IP encapsulation) is a technique to encapsulate IP datagram within IP datagram. This technique allows datagrams destined for one IP address to be wrapped and redirected to another IP address [35], and can be used to build a virtual server. The load balancer encapsulates the request packets and sends them out to the real servers, and the real servers decapsulate and process the requests, and then return the results to the clients directly. As a result, the service can still appear as a virtual service on a single IP address.

In the tunneling mode of the IPVS, the load balancer encapsulates the packet within an IP datagram and forwards it to a dynamically selected server. When the real server receives the encapsulated packet, it decapsulates the packet and finds the inside packet is destined for VIP that is on its tunnel device. Therefore, the real server can return response packets originating from VIP directly to the clients. It should be noted that in the NAT mode, the real servers never know VIP. The author refers to the tunneling mode of the IPVS as IPVS-TUN hereafter in this dissertation.

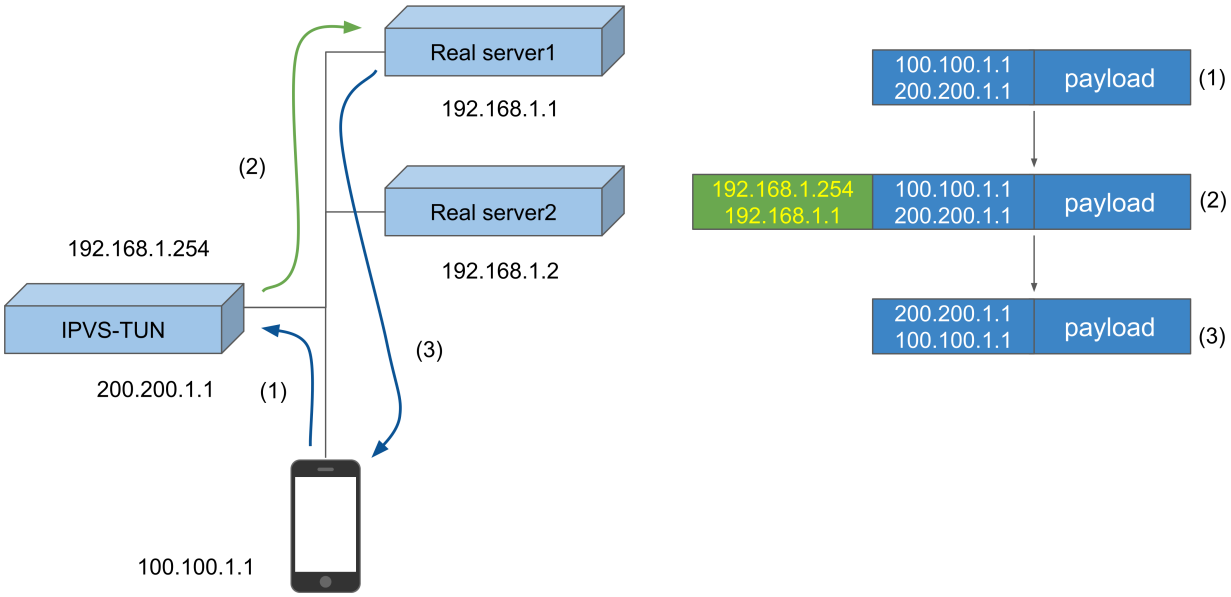


Figure 2.11: Schematic diagram of IPVS tunneling mode. (1) The packet arriving IPVS-TUN enabled host is encapsulated and (2) sent out to one of the real servers. (3) The real server returns the response packets to the client directly.

2.4 XDP technology

In Chapter 5 the author implements a software load balancer using eXpress Data Path (XDP) [38] technology. Here the XDP is briefly explaned.

XDP is a framework to enable injection of a byte-compiled eBPF programs into the NIC driver, so that the program can manipulate a received packet at the earliest point in the Linux networking stack. Therefore much better performance than conventional Linux kernel's network stack is expected. One can create their eBPF program by writing codes in C and then compiling them with Clang using the -march=bpf parameter. The eBPF program injected into the Kernel is just-in-time compiled and used for packet manipulation. XDP merely intercept and process packets only if the packets match the conditions. The packets that do not match the condition are passed through conventional Linux kernel network stack. Therefore there is no need for preparing dedicated NIC for fast and efficient network processing. This is one of the advantages of the XDP technology, compared with the technology using Data Plane Development Kit (DPDK) [39]. Use cases for XDP include DDoS protection, packet forwarding, and load balancing, flow sampling, monitoring, etc.

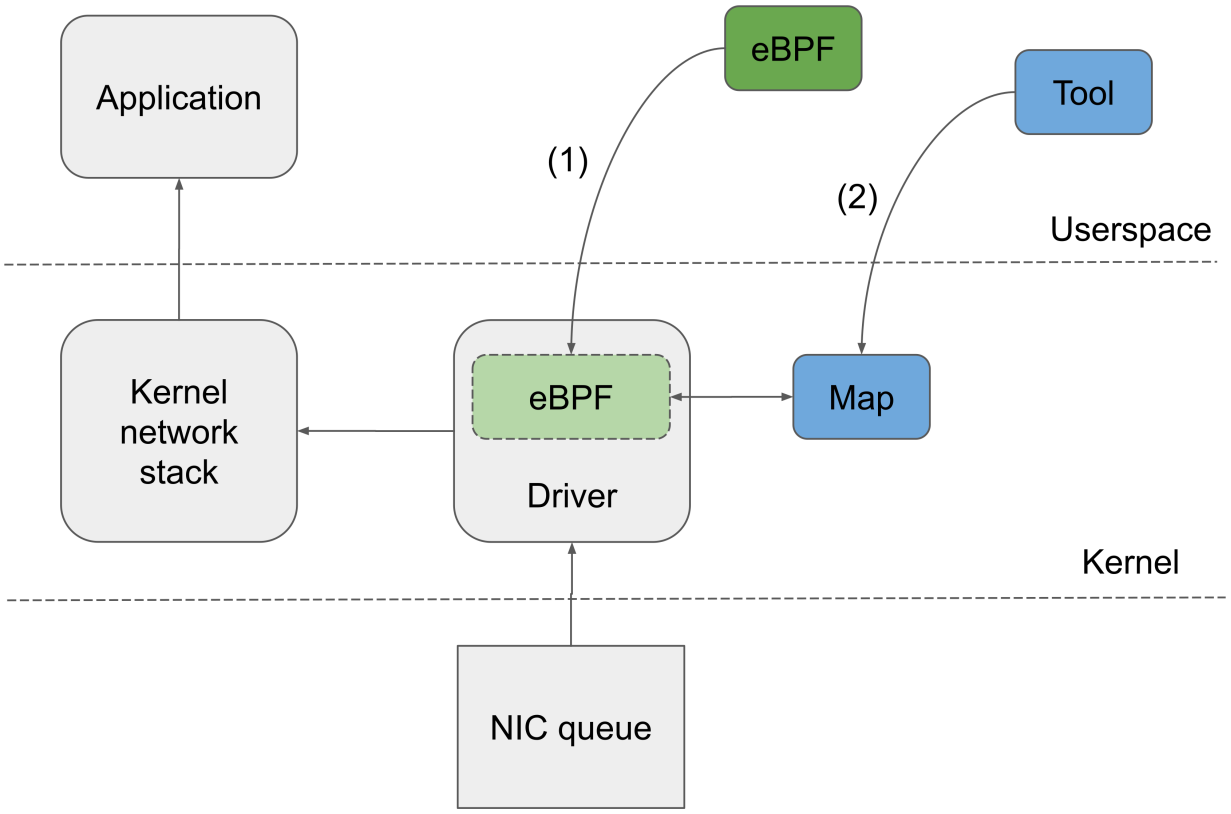


Figure 2.12: XDP architecture. In XDP, user can inject self-made byte-compiled eBPF code in the NIC driver and let it process the incoming packets much earlier than the kernel's network stack. The eBPF programs can make a map inside the kernel, and read/store temporal data from that map. The map is mount at "/sys/fs/bpf/". User can manipulate the behaviour of the eBPF through this map.

2.5 Summary

This chapter provided explanations of the following technologies; 1) Overlay network 2) Multicore packet processing 3) IPVS load balancer 4) XDP technology. These are the underlying technologies used in this study, and knowledge of these is necessary to understand the contents of this thesis.

Overlay networks are used to deploy Kubernetes clusters, and its operation mode greatly affects the throughput of the load balancers. Therefore, they have been explained here. The Linux kernel comes with built-in features for multi-core packet processing. However, the setting might not be optimized for the best performance, and lack of knowledge might hinder the understanding of the experimental results. Therefore, this technology has also been explained. The Linux kernel's IPVS is also necessary to be understood because this is one of the core technologies used in this study, and thus included here. The author plans to replace IPVS based load balancer with the one based on XDP technology in order to improve the performance to meet 100 Gbps level in future work. The explanation of XDP technology is also necessary to understand why it is supposed to be faster than IPVS.

Chapter 3

Architecture and Implementation

Refine Intro of this chapter

One of the most important problems of existing container orchestrators is that none of them has full support for automatically setting up routes for ingress traffic in a redundant and scalable manner. In order to solve this problem, the author proposes a cluster of software load balancer in containers, which is deployed as a part of the web application clusters. Key features required for such load balancers are; 1) to implement a mechanism where the routing table of the upstream router is updated automatically so that the router can forward ingress traffic to running load balances. 2) to implement software load balancer in a container that is runnable in any environment while having the feature to instantly update load balancing tables so that it can forward the packets to running web application containers.

This chapter provides a discussion of such load balancer architecture. First, the author discusses problems of conventional architecture in Section 3.1.1. Then the author proposes a portable software load balancer in a container in Section 3.1.2, and discusses redundancy architecture using ECMP in Section 3.1.3. The author also presents an implementation of the proof of the concept system for the proposed load balancer architecture in detail. The first overall architecture is explained in Section 3.2.1. Then IPVS containerization is explained in detail in Section 3.2.2. Finally, the implementation of BGP software container is explained in Section 3.2.3.

3.1 Architecture

In this section the author discusses the architecture of a portable load balancer for container clusters.

3.1.1 Problem of Conventional Architecture

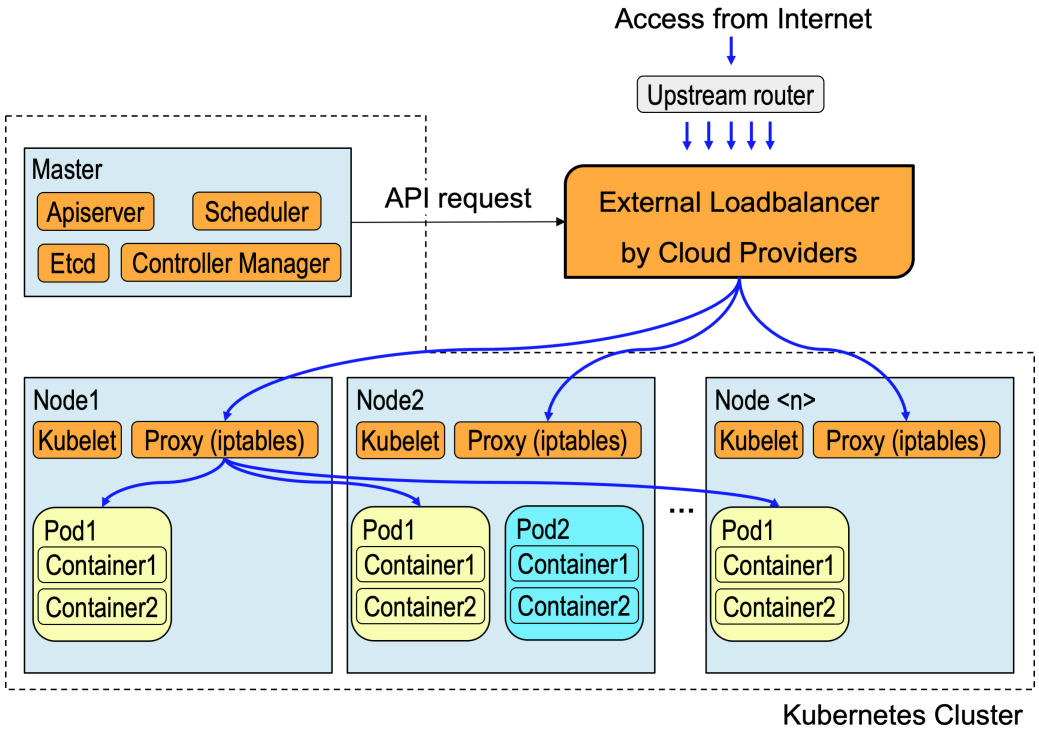
The problem of Kubernetes is its partial support for the ingress traffic routing. Figure 3.1(a) shows an exemplified Kubernetes cluster. When a service is created, the master schedules where to run *pods*, and kubelets on the nodes launch them accordingly. At the same time, the master sends out requests to cloud provider's API endpoints, asking them to set up external cloud load balancers that distribute ingress traffic to every node in the Kubernetes cluster. The proxy daemon on the nodes also setup iptables DNAT [28] rules as an internal load balancer. The Ingress traffic will then be evenly distributed by the cloud load balancer to all of the existing nodes, after which it will be distributed again by the DNAT rules on the nodes to the designated *pods*. The returning packets follows the exact same route as the incoming ones.

This architecture has the followings problems: 1) There must exist cloud load balancers whose APIs are supported by the Kubernetes daemons. There are numerous load balancers which is not supported by the Kubernetes. These include the hardware load balancers for on-premise data centers. 2) Distributing the traffic twice, first on the external load balancers and second on each node, complicates the administration of packet routing. Imagine a situation in which the DNAT table on one of the nodes malfunctions. In such a case, only occasional timeouts would be observed, and hence it would be very difficult to find out which node is malfunctioning. 3) The ingress traffic is distributed to all the existing nodes in the Kubernetes cluster. If there are 1,000 nodes and one of the web applications only uses 10 nodes, distributing the ingress traffic to all of the

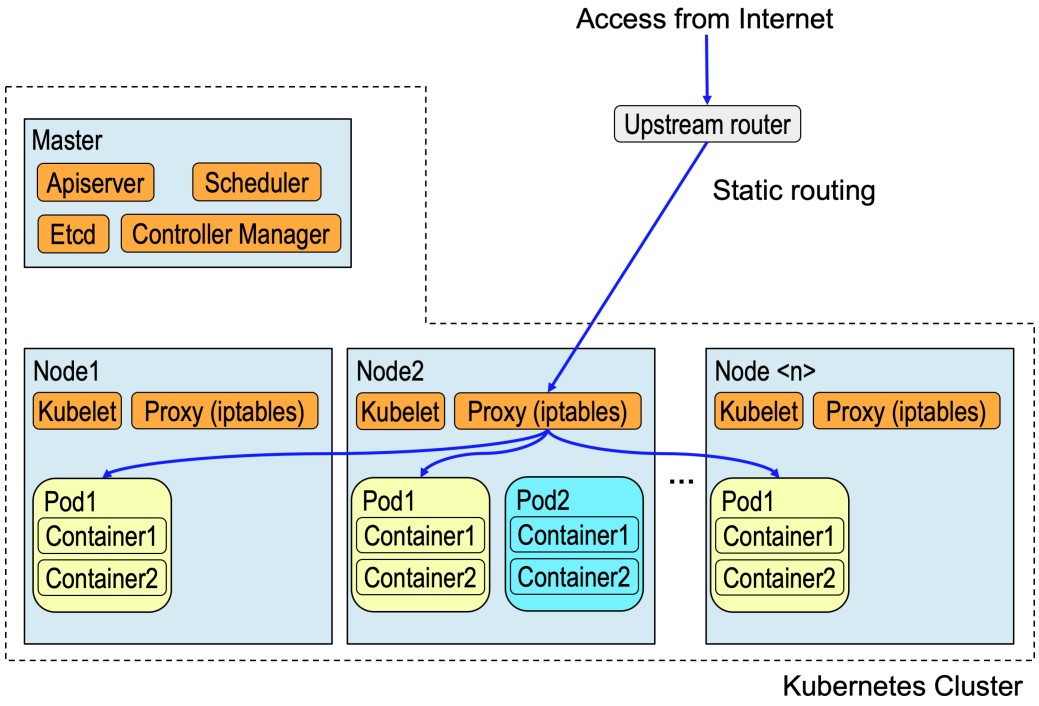
1,000 nodes seems inefficient and complicated.

Regarding the first problem, if there is no load balancer that is supported by Kubernetes, users must manually set up the static route on the upstream router, every time they launch the web application clusters, as is shown in Figure 3.1(b). The traffic will be routed to a node and then distributed by the DNAT rules on the node to the designated *pods*. In cases where the upstream router is administered by a data center company, users must always negotiate with them about adding a route to their new application cluster. This approach significantly lacks simplicity, and degrades the portability of container clusters. Furthermore, a static route usually lacks redundancy and scalability.

In short, while Kubernetes is effective in major cloud providers, it fails to provide portability for container clusters in environments where there is no supported load balancer. And the routes incoming traffic follow are very complex and inefficient. In order to address these problems, the author proposes a containerized software load balancer that is deployable as a part of web application cluster and hence enables users to set up ingress route automatically in any environment even if there is no external load balancer.



((a)) Kubernetes in cloud infrastructures



((b)) Kubernetes in on-premise data centers

Figure 3.1: Conventional architecture of Kubernetes clusters in cloud infrastructure and on-premise data center. (a) In supported infrastructures, e.g., major cloud providers, Kubernetes automatically set up the routes for ingress traffic with the help of the external load balancer. The load balancer distributes ingress traffic to all of the existing nodes. (b) In unsupported infrastructures, e.g., on-premise data centers, web application providers have to manually set up a route to one of the nodes. Packets that reached any of the nodes will be distributed to appropriate pods by the iptables DNAT based internal load balancer.

3.1.2 Load balancer in container

The author proposes a load balancer architecture, where a cluster of load balancer containers is deployed as a part of web application cluster. Figure 3.2 shows the proposed load balancer architecture for Kubernetes, which has the following characteristics; 1) A cluster of load balancer containers is deployed as a part of web application cluster. 2) Each load balancer itself is run as a *pod* by Kubernetes. 3) Load balancing rules are dynamically updated based on the information about running *pods*, which is periodically populated by communicating with apiserver on the master. 4) There exist multiple load balancers for redundancy and scalability. 5) The routing table in the upstream router is updated dynamically using standard network protocol, BGP.

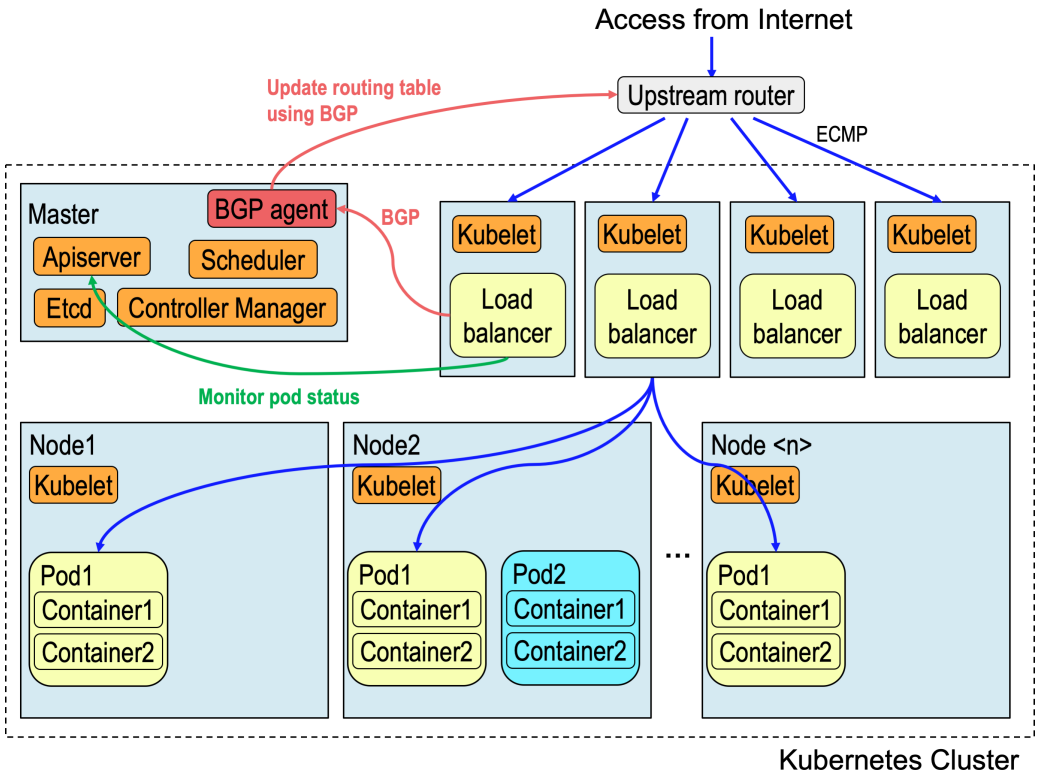


Figure 3.2: Kubernetes cluster with proposed load balancer.
A cluster of load balancer containers is deployed as a part of web application cluster. Each load balancer itself is run as a *pod* in the Kubernetes cluster. Load balancing rules are dynamically updated based on the information about running *pods*. There exist multiple load balancers for redundancy and scalability. The routing table in the upstream router is updated dynamically using standard network protocol, BGP.

The proposed load balancer can resolve the conventional architecture problems. Since the load balancer itself is containerized, the load balancer can run in any environment including on-premise data centers, even without external load balancers that is supported by Kubernetes. The incoming traffic is directly distributed to designated *pods* by the load balancer. It makes the administration, e.g. finding malfunctions, easier. Since the proposed load balancers are deployed as a part of web application cluster and the routes to the load balancers are set up automatically through BGP, users do not need to manually set up a static route to a load balancer.

Furthermore, the proposed load balancer has other benefits. Since a software load balancer in a container can run on any Linux system, it can share the server pool with web containers. Users can utilize existing servers rather than buying dedicated hardware.

Because a cluster of load balancer containers is controlled by Kubernetes, it becomes redundant and

scalable. Kubernetes always tries to maintain the number of load balancer containers as same as the number specified by the user. If a single container fails, Kubernetes schedule and launch another one on a different node, which provides the resilience to failures. When there is a huge spike in the traffic, user can quickly scale the size of the cluster depending on the demand.

The routes to the load balancers are automatically updated through the standard protocol, BGP. Therefore users do not need to manually add the route every time new load balancer container is launched, as is the case in the conventional architecture.

3.1.3 Redundancy with ECMP

While containerizing IPVS makes it runnable in any environment, it is essential to discuss how to route the ingress traffic to the IPVS container. The author proposes redundant architecture using ECMP with BGP for proposed load balancer containers.[1] The BGP and ECMP are both standard protocols supported by most of the commercial router products, and they are used for cloud load balancers as well [16, 17]. However, in the case of container environments, where overlay networks are often used, special cares are needed to make the mechanism work properly.

Fig. 3.3 shows a schematic diagram to explain redundancy architecture with ECMP for the proposed load balancer. The ECMP is a functionality a router supports, where the router has multiple next hops with equal priority (cost) to a destination. And the router generally distributes the traffic to the multiple next hops depending on the hash of five-tuples (source IP, destination IP, source port, destination port, protocol) of the flow. The multiple next hops and their cost are often populated using the BGP protocol. The notable benefit of the ECMP setup is its scalability. All the load balancers that claims as the next hop is active, i.e., all of them are utilized to increase the performance level. Since the traffic from the internet is distributed by the upstream router, the overall throughput is, after all, limited by performance levels of the router. However, in practice, there are a lot of cases where this architecture is beneficial. For example, if a software load balancer is capable of handling 1 Gbps equivalent of traffic and the upstream router is capable of handling 10 Gbps, it still is worthwhile launching 10 of the software load balancer containers to fill up maximum throughput of the upstream router.

In the proposed redundant architecture, there exists a node with the knowledge of the overlay network as a route reflector. A route reflector is a network component for BGP to reduce the number of peerings by aggregating the routing information [40]. In the proposed architecture the author uses it as a delegater for load balancer containers towards the upstream router.

The route reflector exists for a practical reason, i.e, to deal with the complexity due to the overlay network. Since the upstream router normally has no knowledge of the overlay network and IP addresses used inside the Kubernetes clusters, a container must rely on SNAT on the node to communicate with the router. The SNAT caused a problem when the author tried a set up without the route reflector, to co-host multiple load balancer containers for different services on a single node. Because of the SNAT, the source IP addresses of multiple connections were translated into a single IP address possessed by the node. The BGP agent on the router was confused by these connections and could not properly set up ECMP routes for separate services. This was due to the fact that the BGP agent used in the experiment used only the source IP address of the connection to distinguish the BGP peer.

In addition to alleviate complexiety due to overlay network, the route reflector brings another benefit. By using the route reflector, the upstream router no longer needs to accept BGP sessions from containers with

[1] The author also investigated redundancy architecture using VRRP in Appendix D. However, VRRP had limitation in overlay networks used for container clusters.

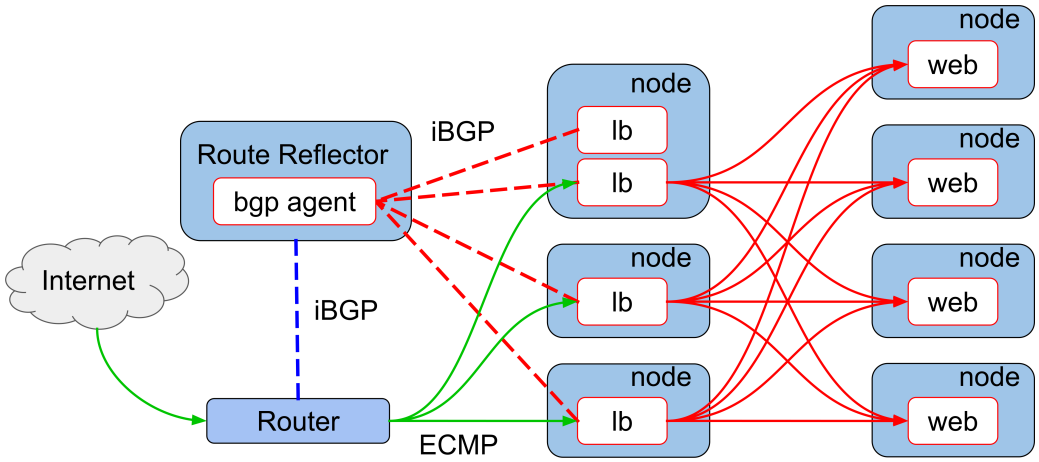


Figure 3.3: The proposed architecture of load balancer redundancy with ECMP
The traffic from the internet is distributed by the upstream router to multiple of load balancer (lb) pods using hash-based ECMP (the solid green line), after which distributed by the lb pods to web pods using Linux kernel's IPVS (the solid red line). The route toward a service IP is advertised to the route reflector (the dotted red line), after which advertised to the upstream router (the blue dotted line) using iBGP.

random IP addresses, but only from the route reflector with well known fixed IP address. This is preferable in terms of security especially when a different organization administers the upstream router.

By using the route reflector, we can have the following benefits. 1) Each node can accommodate multiple load balancer containers. This was not possible when the author tried to directly connect load balancers and the router through SNAT. 2) The router does not need to allow peering connections from random IP addresses that may be used by load balancer containers. Now, the router only need to have the reflector information in the BGP peer definition.

Since a standard Linux system is used for the route reflector, it can be configured as we like; a) It can be configured to belong to the overlay network so that multiple BGP sessions from containers on a single node can be properly distinguished. b) One can select a BGP agent that supports dynamic neighbor (or dynamic peer), where he only needs to define the IP range as a peer group and does away with specifying every possible IP that load balancers may use. Although not shown in the Fig. 3.3, it is possible to have another route reflector for redundancy purpose. It is also possible to make the master node of Kubernetes also act as the route reflector.

3.2 Implementation

In this section the author discusses the implementation of the experimental system to prove the concept of the proposed load balancers with ECMP redundancy in detail.

3.2.1 Experimental system architecture

Figure 3.4 shows the schematic diagram of proof of concept container cluster system with the proposed software load balancers. Each load balancer pod consists of an exabgp [41] container and an IPVS container. The IPVS container is responsible for distributing the traffic toward the service IP to web server (nginx) pods. The IP address for nginx pods and load balancer pods are dynamically assigned upon launch of themselves from 172.16.0.0/16 address range. The IPVS container monitors the availability of web server pods by consulting apiserver on the master node and manages the load balancing rule appropriately. The exabgp

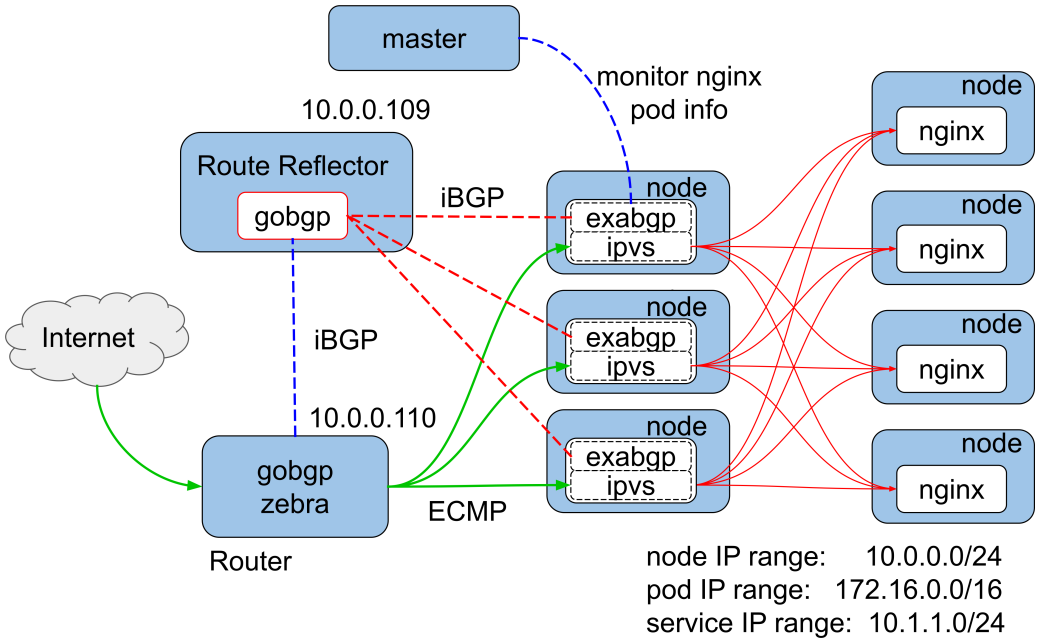


Figure 3.4: An experimental container cluster with proposed redundant software balancers. The master and nodes are configured as Kubernetes's master and nodes on top of conventional Linux systems, respectively. The route reflector and the upstream router are also conventional Linux systems. For the green lines, a service IP address is used. The red lines use the IP addresses of the overlay network. The blue line uses the IP addresses of the node network.

container is responsible for advertising the route toward the service IP to the route reflector using BGP. The route reflector aggregates the routing information advertised by load balancer pods and advertise them to the upstream router. The upstream router updates its routing table according to the advertisement.

All the nodes and route reflector are configured using Debian 9.5 with self compiled linux-4.16.12 kernel. The author also used conventional Linux system as an upstream router for testing purpose, using the same OS as the nodes and the route reflector. The version of Linux kernel needed to be 4.12 or later to support hash based ECMP routing table. The author also needed to enable kernel config option CONFIG_IP_ROUTE_MULTIPATH [42] when compiling, and set the kernel parameter fib_multipath_hash_policy=1 at run time. Although in the actual production environment proprietary hardware router with the highest throughput is usually deployed, one can still test some of the advanced features by using a conventional Linux system for the upstream router.

Features	gobgpd	exabgp	bird
Static route advertisement	complex	simple	complex
Add-path support*	Yes	No	Yes
Dynamic neighbor**	Yes	No	No
FIB manipulation	Yes (through zebra)	No	Yes (Native)

Table 3.1: Comparison of open source BGP agents. Open source BGP agents are compared in terms of the features required in the proposed systems.
* The add-path is the feature to support multipath advertisement.
** The dynamic-neighbor is the feature to describe peer group as a range of IP address.

Table 3.1 compares open source BGP agents in terms of required features for the proposed architecture. Each load balancer *pod* needs to advertise itself as the next hop for packets toward the service IP. For that purpose, exabgp is preferable because it only requires to add a line, e.g., "route [Service_IP] next-hop [Pod_IP]"

in the configuration file. On the other hand, the gobgpd and the bird require other client programs to inject the static route after the daemon itself is up and running. For example, in the case of gobgpd, after launching gobgpd, a user is required to issue a command line, e.g., "gobgp global rib add [Service_IP]/32 origin igp nexthop [Pod_IP] community 100:50 -a ipv4". (The gobgp is a client program to manage gobgpd.) This is a bit complex and error-prone, especially when one has to inject the route periodically inside a container.

As for the route reflector, add-path [18] feature and dynamic neighbor feature are needed. These are supported by gobgpd. For the upstream router Forwarding Information Base (FIB) manipulation [41] feature is needed, which is supported by gobgpd through zebra [43, 44]. As a result, exabgp is used for the load balancer pods, gobgpd is used for the route reflector, and gobgpd and zebra are used for the upstream router.

The other requirement for the route reflector is the knowledge of the overlay network for the containers. The configurations for the upstream router is summarised in Appendix B.2. The configurations for the route reflector is summarised in Appendix B.3.

3.2.2 IPVS container

In order to implement a software load balancer that is runnable in any environment, the author used Linux kernel's IPVS in Docker container. In addition to that, the proposed load balancer uses two other components, keepalived, and a controller. These components are placed in a single Docker container image. The Dockerfile, a shell script file and the template files used to create the load balancer container are shown in Appendix **??**. The IPVS is a Layer-4 load balancer capability, which is included in the Linux kernel 2.6.0 released in 2003 or later, to distribute incoming Transmission Control Protocol (TCP) traffic to *real servers*[2] [20]. For example, IPVS distributes incoming Hypertext Transfer Protocol (HTTP) traffic destined for a single destination IP address, to multiple HTTP servers (e.g. Apache HTTP or nginx) running on multiple nodes in order to improve the performance of web services. Keepalived is a management program that performs health checking for *real servers* and manages IPVS balancing rules in the kernel accordingly. It is often used together with IPVS to facilitate ease of use. The controller is a daemon that periodically monitors the *pod* information on the master, and it performs various actions when such information changes. Kubernetes provides ingress controller framework as the Go Language (Golang) package to implement the controllers. The author implemented a controller program that feeds *pod* state changes to keepalived using this framework (Appendix A).

The proposed load balancer needs to dynamically reconfigure the IPVS balancing rules whenever *pods* are created or deleted. Figure 3.5 is a schematic diagram of IPVS container to show the dynamic reconfiguration of the IPVS rules. Two daemon programs, controller and keepalived, running in the container are illustrated. The keepalived manages Linux kernel's IPVS rules depending on the ipvs.conf configuration file. It can also periodically check the liveness of a *real server* which is represented as a combination of the IP addresses and port numbers of the target *pods*. If the health check to a *real server* fails, keepalived will remove that *real server* from the IPVS rules immediately. The interval of the health check is typically 1 to several seconds and is arbitrarily determined by users.

Every second, the controller monitors information concerning the running *pods* of a web application in the Kubernetes cluster by consulting the apiserver running in the master through its API. Whenever *pods* are created or deleted, the controller notices the change and automatically regenerate an appropriate ipvs.conf and issue SIGHUP to keepalived within a second. Then, keepalived will reload the ipvs.conf, and modify the IPVS rules inside the kernel appropriately depending on the result of the health check.

When a pod is terminated, existing connections are reset by the node kernel. The SYN packets sent to a

[2]The term, *real servers* refers to worker servers that will respond to incoming traffic, in the original literature [20]. The author will also use this term in a similar way.

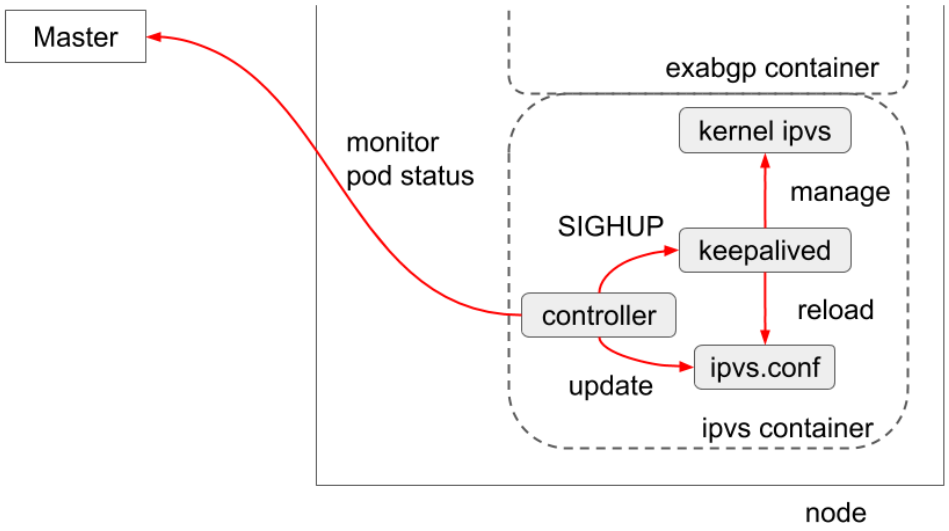


Figure 3.5: Implementation of IPVS container. The controller checks the pod status every second, by consulting the master node. Upon a change of the status, the controller updates the ipvs.conf and sends SIGHUP to keepalived. The keepalived reload the ipvs.conf and updates the load balancing rules in the kernel correctly.

pod after termination, but before the IPVS rule update, will be answered with ICMP unreachable by the node. In these cases, the client sees connection errors.

However, since the load balancer rule update is within a second, these errors can be regarded as the tolerable rare exceptions. In order to avoid the connection errors to be seen by a human, HTTP client programs are required to re-initiate the connection.

The actual controller [45] is implemented using the Kubernetes ingress controller [46] framework. By importing existing Golang package, "k8s.io/ingress/core/pkg/ingress", the author could simplify the implementation, e.g. 120 lines of code (Appendix A). Keepalived and the controller are placed in the docker image of IPVS container. The namespace separation for IPVS has already been supported in the recent Linux kernel.

Configurations for capabilities were needed when deploying the IPVS container: adding the CAP_SYS_MODULE capability to the container to allow the kernel to load required kernel modules inside a container, and adding CAP_NET_ADMIN capability to the container to allow keepalived to manipulate the kernel's IPVS rules. For the former case, the author also needed to mount the "/lib/module" of the node's file system on the container's file system.

Figure 3.6 and Figure 3.7 show an example of an ipvs.conf file generated by the controller and the corresponding IPVS load balancing rules, respectively. Here, we can see that the packet with `fwmark=1` [47] is distributed to *172.16.21.2:80* and *172.16.80.2:80* using the masquerade mode (Masq) and the least connection (lc) [20] balancing algorithm.

3.2.3 BGP software container

In order to implement the ECMP redundancy, the author also containerized exabgp using Docker. The Dockerfile and a shell script file used to create the BGP software container are shown in Appendix ??. Figure 3.8 shows a schematic diagram of the network path realized by the exabgp container. As mentioned

```
virtual_server fwmark 1 {
  delay_loop 5
  lb_algo lc
  lb_kind NAT
  protocol TCP
  real_server 172.16.21.2 80 {
    uthreshold 20000
    TCP_CHECK {
      connect_timeout 5
  connect_port 80
    }
  }
  real_server 172.16.80.2 80 {
    uthreshold 20000
    TCP_CHECK {
      connect_timeout 5
      connect_port 80
    }
  }
}
```

Figure 3.6: An example of ipvs.conf This configuration file is auto-generated by the controller. The controller periodically accesses the apiserver on the master node and constantly monitor the status of running pods.

```
IP Virtual Server version 1.2.1 (size=4096)
Prot LocalAddress:Port Scheduler Flags
 -> RemoteAddress:Port Forward Weight ActiveConn InActConn
FWM  1 lc
 -> 172.16.21.2:80      Masq    1      0          0
 -> 172.16.80.2:80      Masq    1      0          0
```

Figure 3.7: Example of IPVS balancing rules. This shows the load balancing rule in a load balancer container. The packet that has FWM (fwmark)=1 will be forwarded to two real servers using the least connection (lc) balancing algorithm. The fwmark is a parameter that is only available inside a socket buffer in Linux kernel. The fwmark can be put and manipulated by the iptables program, once a socket buffer for a received packet is assigned by the kernel.

earlier, the author used exabgp as the BGP advertiser. The ingress traffic from the Internet is forwarded by ECMP routing table on the router to the node that hosts a load balancer pod. And then it is routed to the load balancer pod according to the set of routing rules in Table 3.2(2),(3). After that the IPVS forwards them to nginx pods. The IP address of any pod is dynamically assigned from 172.16.0.0/16 when the pod is started.

Table 3.2 summarises some key settings required in the exabgp container to route the traffic to the IPVS container. (1) In BGP announcements the node IP address, 10.0.0.106 is used as the next-hop for the service IPs, 10.1.1.0/24. (2) Then on the node, in order to route the packets toward the service IPs to the IPVS container, a routing rule for 10.1.1.0/24 to the dev docker0 is created in the node net namespace. (3) A routing rule to accept the packets toward the service IPs as local is also required in the container net namespace. The configuration for exabgp is shown in Appendix B.4.

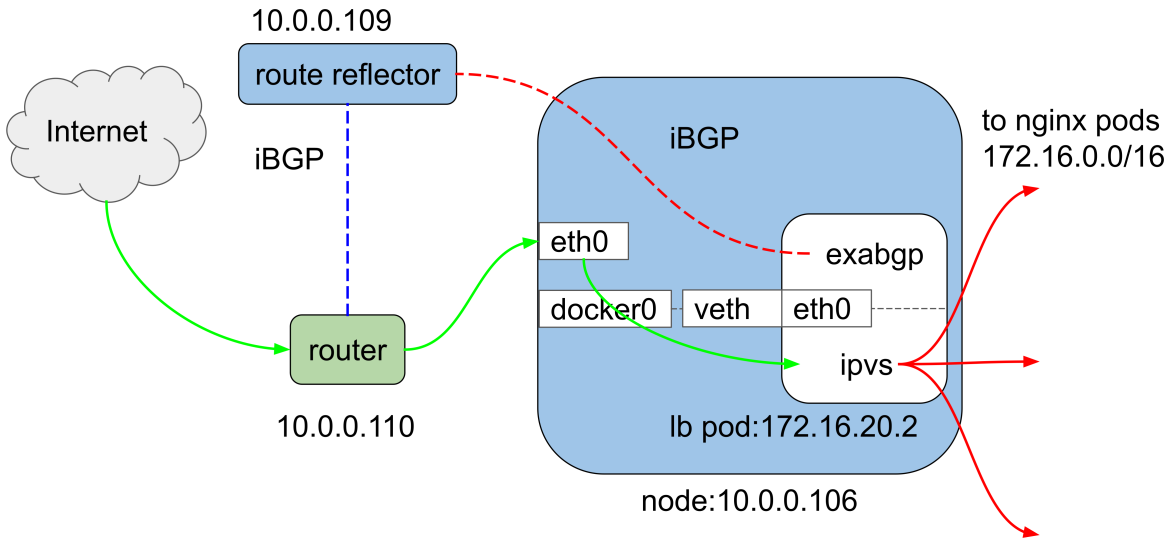


Figure 3.8: Network path by the exabgp container. The packets from Internet to service IPs, 10.1.1.0/24 are routed to the load balancer pod (green arrows) by the set of routing rules shown in Table 3.2. And then the IPVS container forwards them to nginx pods (red arrows). The IP address of any pod is dynamically assigned from 172.16.0.0/16 when the pod is started.

```
[BGP announcement]
   route 10.1.1.0/24 next-hop 10.0.0.106       ...(1)
[Routing in node net namespace]
   ip netns exec node \
      ip route replace 10.1.1.0/24 dev docker0 ...(2)
[Accept as local]
   ip route add local 10.1.1.0/24 dev eth0     ...(3)
```

Table 3.2: Required settings in the exabgp container. (1) The node IP address, 10.0.0.106 is used as next-hop for the service IPs, 10.1.1.0/24, in BGP announcement. (2) In order to route the packets destined toward the service IP to the container, a routing rule to the dev docker0 is created in the node net namespace. (3) A routing rule to accept the packets destined toward the service IPs, as local is also required.

3.3 Summary

In this chapter, the author provided a discussion of load balancer architecture and its implementations suitable for container clusters. First, the author discussed the problems of conventional architecture. Since Kubernetes is dependent on external load balancers provided by the cloud infrastructures, it failed to provide portability of a web application in environments where there was no supported load balancer. Furthermore, the routes that ingress traffic from the internet follow were very complex and inefficient.

In order to alleviate these problems, the author proposed a cluster of software load balancers in containers. The proposed load balancers utilized container technology and were managed by Kubernetes. As a result, it is runnable on any environment including cloud infrastructures and on-premise data centers. Furthermore, since Kubernetes manages load balancer containers, it can quickly scale the number of containers depending on the demand. The author also discussed redundant architecture using ECMP with BGP for proposed load balancer containers. By using the ECMP, the upstream router can route the ingress traffic to a cluster of load balancer containers in a redundant and scalable manner. By using BGP, ECMP routing rules in the upstream router are

automatically populated, upon the launch of load balancer containers. The BGP and ECMP are both standard protocols supported by most of the commercial router products.

Thanks to the proposed load balancer, users become being able to set up routes to their web applications automatically, upon its launch, regardless of the infrastructures they use. This will greatly improve the portability of a web application and thereby enables migrations.

Chapter 4

Performance Evaluation

In this chapter, the author evaluates the feasibility of the proposed load balancer. At first, the author evaluates the basic characteristics of the load balancer using physical servers in the on-premise data center, by comparing the throughput of the load balancer with several experimental conditions. Then the author verifies the feasibility of the proposed load balancer through experiments, with the following criteria; 1) Portability: whether the load balancer can run in both on-premise data centers and cloud infrastructures. 2) Redundancy and scalability: whether the throughput is changed by changing the number of load balancers. 3) Performance: whether the load balancer has sufficient throughput for 1 Gbps network.

4.1 Performance analysis of proposed load balancer

Experimental conditions

Throughput measurements were carried out in order to examine the basic characteristics of the containerized IPVS load balancer in an on-premise data center. Figure 4.1 shows the schematic diagram of the experimental setup for the measurement. A benchmark program called wrk [48] were used. Multiple nginx *pods* are deployed on multiple nodes as web servers in the Kubernetes cluster. In each nginx *pod*, single nginx web server program that returns the IP address of the *pod* itself is running. The author then launched IPVS pod and nginx pod as load balancers on one of the nodes, after that, performed the throughput measurement changing the number of the nginx web server pods. On every Kubernetes node, there are iptables DNAT rules that function as an internal load balancer. The author also measured throughput of this internal load balancer. The throughput is measured by sending out HTTP requests from the wrk towards a load balancer and by counting the number of responses the benchmark client received.

Table 4.1 shows an example of the command-line for the benchmark program, wrk, and the corresponding output. The command-line in Table 4.1 will generate 40 wrk program threads and allow those threads to send out a total of 800 concurrent HTTP requests over the period of 30 seconds. The output example shows information including per-thread statistics, error counts, throughput in [Request/sec] and data rate in [Transfer/sec].

Table 4.2 shows hardware and software configuration used in the experiment. The author used a total of eight servers; six servers for Nodes, one for the load balancer and one for the benchmark client, with all having the same hardware specifications. The hardware had eight physical CPU cores and a network interface card (NIC) with four rx-queues. The author configured nginx HTTP server to return a small HTTP content, the IP address of the *pod*, to make a relatively severe condition for load balancers. The size of the character string making up an IP address is limited to 15 bytes.

The author also measured throughputs of the load balancers varying two types of network conditions: The first condition is the setting for multicore packet processing. It is known that distributing handling of interrupts from the NIC and the subsequent IP protocol processing among multiple cores improve the network throughput of a Linux machine. To derive the best performance from load balancers, the author investigated how this setting would affect their performance levels. The second condition is the overlay

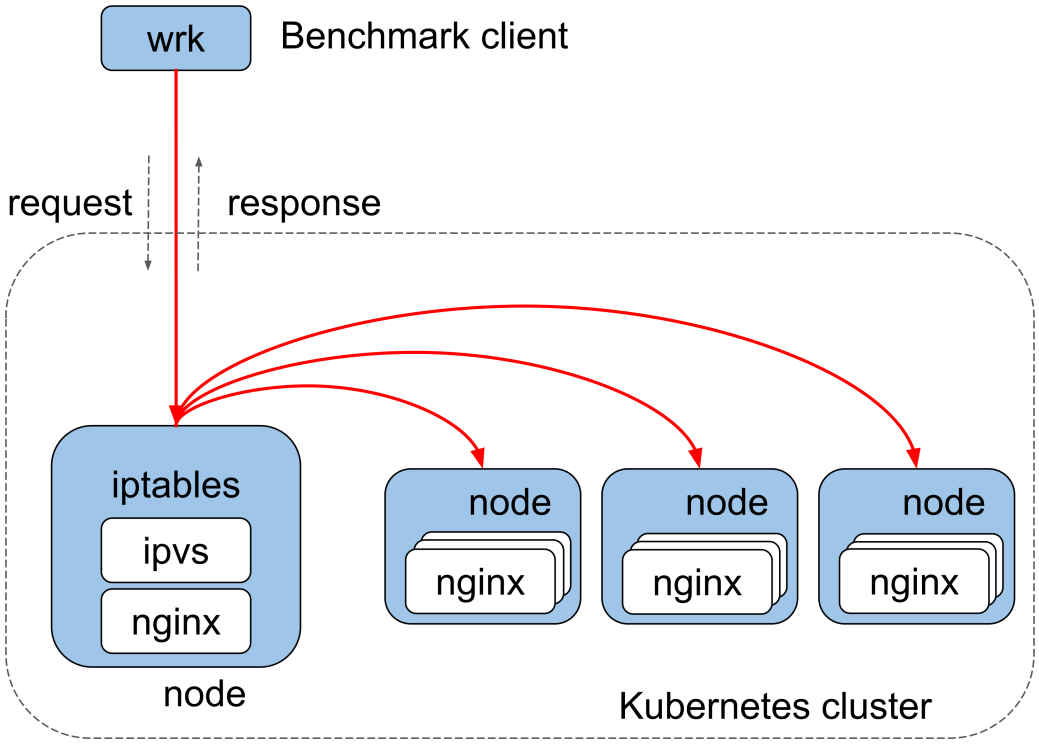


Figure 4.1: Benchmark setup. There are nodes on which nginx pods are deployed as web servers. There is another node where IPVS pod and nginx pod are deployed. Iptables DNAT rules exist on every Kubernetes node as an internal load balancer. Throughput measurements are performed against IPVS pod, nginx pod, and iptables DNAT rules. Each of the load balancers distributes the packets from the wrk to the nginx web servers. The response packets from the nginx web servers follow the same route as the request packets.

network settings [49, 25]. An overlay network is often used to build the Kubernetes cluster and therefore used in the experiment. The author used flannel [30], which is one of the popular overlay network technologies. The author compared the throughputs of three backend modes [33] of flannel to find the best setting.

```
wrk -c800 -t40 -d30s http://172.16.72.2:8888/
    -c: concurrency, -t: # of thread, -d: duration
```

(a) Command line

```
Running 30s test @ http://10.254.0.10:81/
  40 threads and 800 connections
  Thread Stats   Avg      Stdev     Max   +/- Stdev
    Latency    15.82ms   41.45ms   1.90s    91.90\%
    Req/Sec     4.14k   342.26     6.45k    69.24\%
  4958000 requests in 30.10s, 1.14GB read
  Socket errors: connect 0, read 0, write 0, timeout 1
Requests/sec: 164717.63
Transfer/sec:     38.86MB
```

(b) Output example

Table 4.1: Benchmark command line and output example. (a) This command line will generate 40 wrk program threads and allow those threads to send out a total of 800 concurrent HTTP requests over the period of 30 seconds. (b) The output example shows information including per-thread statistics, error counts, throughput in [Request/sec] and data rate in [Transfer/sec]. The throughput is 164717.63 [Request/sec] in this example.

```
[Hardware Specication]
   CPU: Xeon E5-2450 2.10GHz (with 8 core, Hyper Threading)
   Memory: 32GB
   NIC: Broadcom BCM5720 with 4 rx-queues, 1 Gbps
   (Node x 6, Load Balancer x 1, Client x 1)

[Node Software]
   OS: Debian 8.7, linux-3.16.0-4-amd64
   Kubernetes v1.10.6
   flannel v0.7.0
   etcd version: 3.0.15

[Container Software]
   Keepalived: v1.3.2 (12/03,2016)
   nginx : 1.11.1 (load balancer), 1.13.0 (web server)
```

Table 4.2: Hardware and software specifications. The hardware had eight physical CPU cores and a network interface card (NIC) with four rx-queues.

Effect of multicore processing

Figure 4.2 shows the result of the throughput measurement for the IPVS load balancer with different multicore processing settings. Since hardware used in the experiment has a NIC with four rx-queues, and a CPU with eight cores, the setting "(RSS, RPS) = (on, off)" uses four cores and "(RSS, RPS) = (off, on)" uses eight cores for packet processing respectively. For the setting "(RSS, RPS) = (off, off)", only one core is used for the packet processing.

There is a general trend in the throughput result, where the throughput linearly increases as the number of nginx *pod*s increases and then it eventually saturates. For example, if we look at the red line in the Figure 4.2, the throughput increases almost linearly as the number of the nginx pods (web servers) increases from 1 to around 14, and then saturates. The increase indicates that the load balancer functions properly, as the load balancer increased throughput by distributing HTTP requests to multiple of the web servers. The saturated throughput indicates the maximum performance level of the load balancer, which could be determined either by network bandwidth between the benchmark client and the load balancer node, or CPU performance levels of these machines. The maximum performance levels are dependent on the number of cores used for packet processing. Throughput is highest for the setting with eight cores (rps = on), followed by four cores (rss = on), then single core (none). This indicates that the more cores are used, the better the throughput is.

Figure 4.3 shows the result of the throughput measurement for iptables DNAT as a load balancer, with different multicore processing settings. As is the case for the IPVS result, there is a general trend where the throughput increases as the number of nginx *pod*s increases and then it eventually saturates. Also, throughput is highest for the setting with eight cores (rps = on), followed by four cores (rss = on), then single core (none). The saturated performance levels of iptables DNAT and IPVS are the same for the condition with eight cores (rss = on). The saturated performance levels of iptables DNAT are higher than those of IPVS, for the conditions with four cores (rss = on) and single core (none).

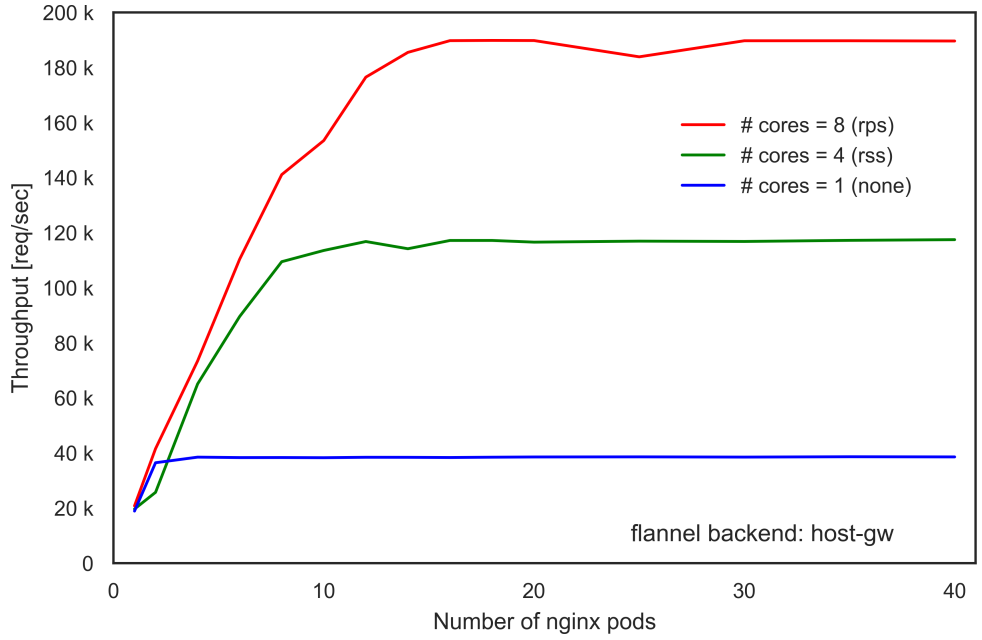


Figure 4.2: Effect of multicore packet processing on IPVS throughput. Throughput linearly increases as the number of nginx *pod*s increases and then it eventually saturates. The throughput is highest for the setting with eight cores (rps = on), followed by four cores (rss = on), then single core (none).

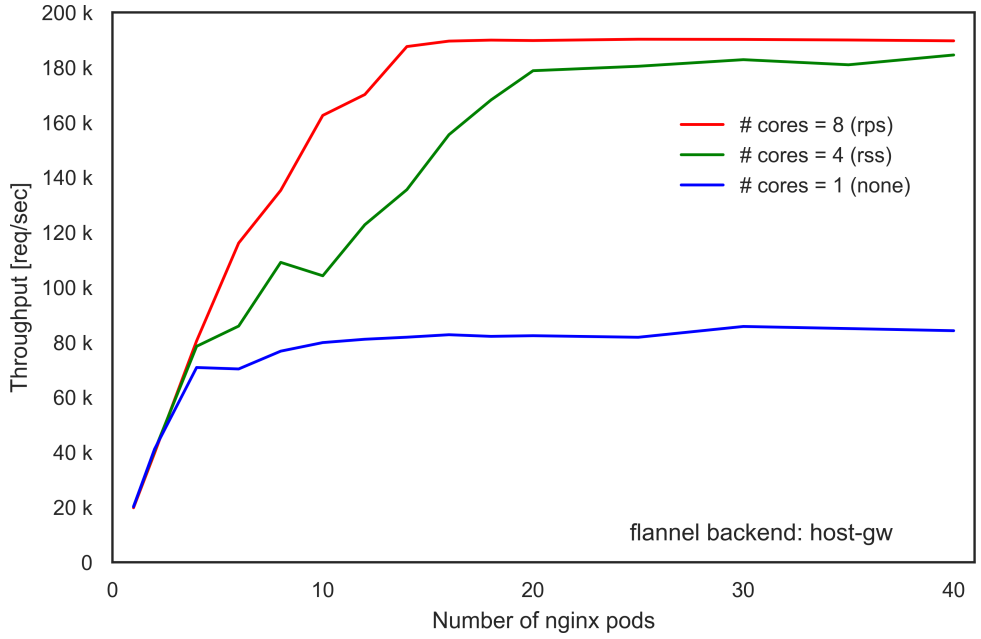


Figure 4.3: Effect of multicore packet processing iptables DNAT throughput. Throughput linearly increases as the number of nginx *pod*s increases and then it eventually saturates. The throughput is highest for the setting with eight cores (rps is on), followed by four cores (rss is on), then single core (none).

Effect of overlay network

Figure 4.4 shows the IPVS throughput results for different overlay network settings. The author used the flannel for the overlay network. Flannel has three backend modes, host-gw, vxlan and udp, and the throughput for each setting are compared.

Except for the udp backend mode case, a general trend can be clearly seen, i.e., the throughput linearly increases as the number of nginx *pod* increases, and then it eventually saturates. Among the flannel backend mode types, the host-gw mode where no encapsulation is conducted shows the highest performance level, followed by the vxlan mode where the Linux kernel encapsulates the Ethernet frame. The udp mode where flanneld itself encapsulates the IP packet shows significantly lower performances levels.

Figure 4.5 shows throughput results of the iptables DNAT as a load balancer for different overlay network settings. The same characteristics can be seen for the iptables DNAT, although the performance level of the iptables DNAT for udp mode is slightly better than that of IPVS.

As is shown here, overlay network settings greatly affect the performance level. The author considers the host-gw mode is the best, the vxlan tunnel the second best and the udp tunnel mode unusable. In environments where containers need to communicate with each other via a gateway that has no knowledge of overlay network, the backend modes with tunneling are inevitable, which is often the case in cloud environments. The author used vxlan mode for the experiments conducted in cloud environments and host-gw mode for the rest of the experiments conducted in on-premise data centers.

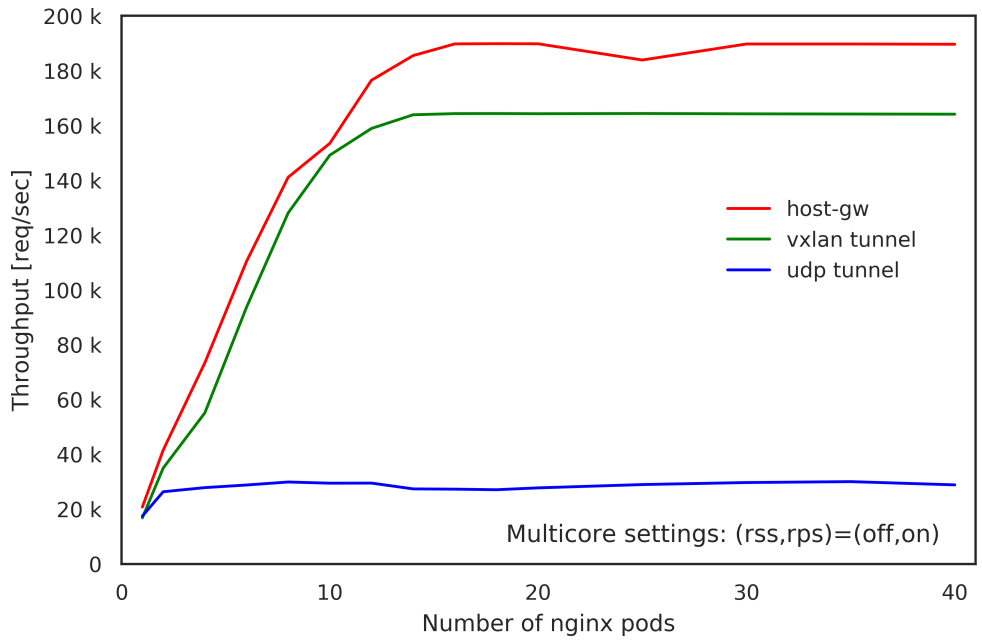


Figure 4.4: Effect of flannel backend modes on IPVS throughput. The host-gw mode shows the highest performance level, followed by the vxlan mode. The udp mode shows significantly lower performances levels.

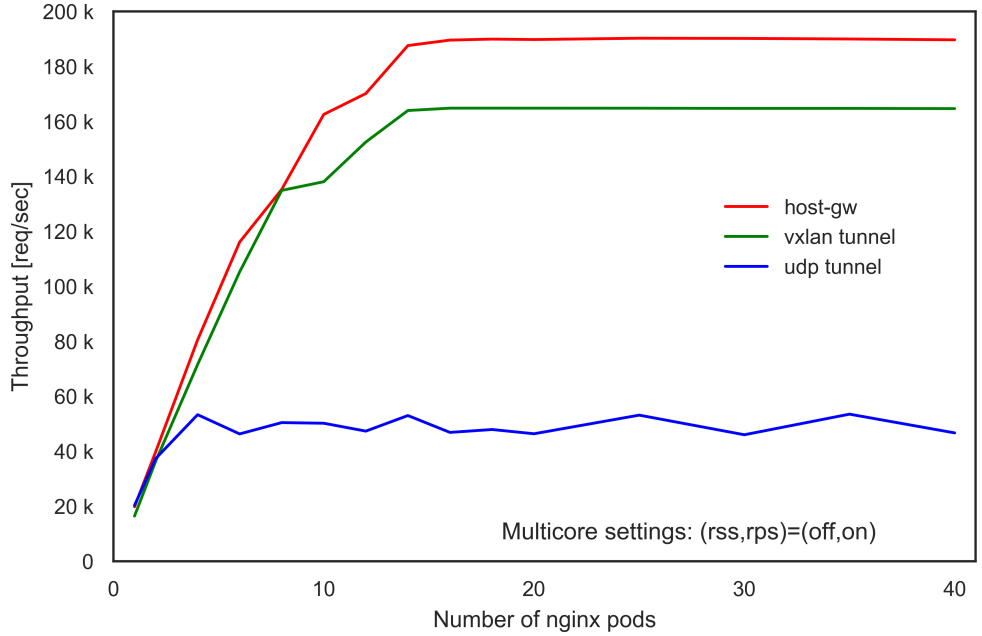


Figure 4.5: Effect of flannel backend modes on iptables DNAT throughput. the host-gw mode shows the highest performance level, followed by the vxlan mode. The udp mode shows significantly lower performances levels.

Comparison of different load balancer

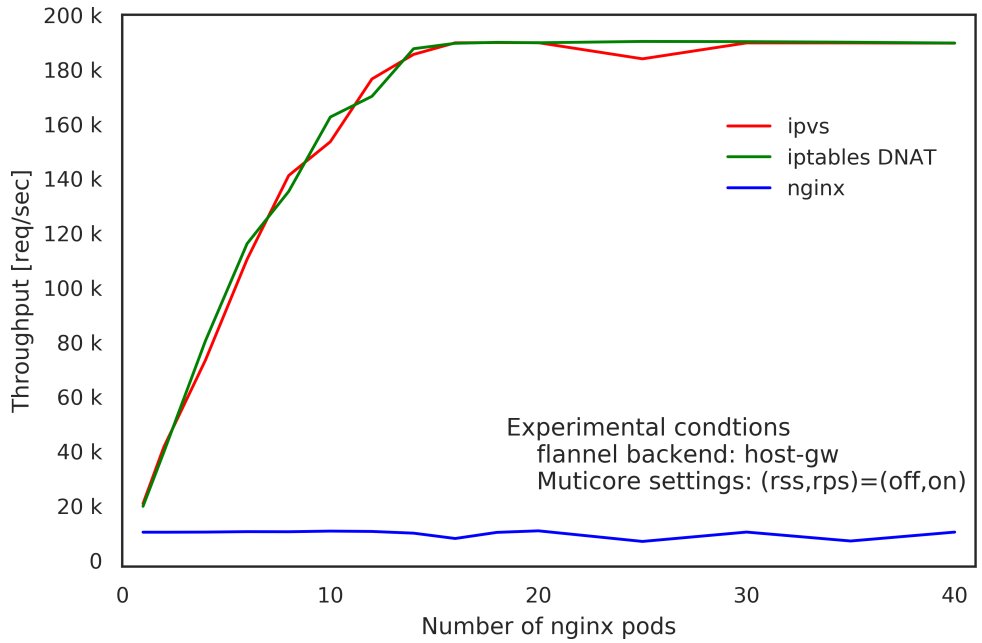


Figure 4.6: Throughput of IPVS, iptables DNAT and nginx. The performance levels of IPVS and iptables DNAT are almost the same. The nginx as a load balancer does not perform well in the experiment.

Figure 4.6 presents the throughput results of the different load balancers. The performance levels of IPVS, iptables DNAT and nginx as the load balancers are compared. The throughput of the IPVS and iptables DNAT increases almost linearly as the number of nginx pods (web servers) increase from 1 to around 14, and then it saturates. The proposed IPVS load balancer exhibits almost equivalent performance levels as the iptables DNAT as a load balancer.

The saturated throughput indicates the maximum performance level of the load balancer, which could be determined either by network bandwidth between the benchmark client machine and the load balancer node, or CPU performance levels of these machines. In this specific experiment, it was found that the performance levels of IPVS and iptables DNAT were limited by the 1 Gbps network bandwidth at the load balancer node.[1]

This was revealed by packet-level analysis using tcpdump (Appendix C). On average the data size of each request and the corresponding response was about 636 [byte/req] in total, including TCP/IP headers, Ethernet header, and inter-frame gaps. Multiplying that with 190K [req/sec] and 8 [bit/byte] will result in 966.72 Mbps. Therefore the throughput of about 190K [req/sec] is a reasonable number as the maximum performance level in 1Gbps network environment.

Figure 4.7 compares Cumulative Distribution Function (CDF) of the load balancer latency at the two constant loads, 160K[req/sec] and 180K[req/sec] for IPVS and iptables DNAT. It is seen that the latencies are a little bit smaller for IPVS. For example, the median values at 160K[req/sec] load for IPVS and iptables DNAT are, 1.14 msec and 1.24 msec, respectively. Also, at 160K[req/sec], they are 1.39 msec and 1.45 msec, respectively. While these may be considered a subtle difference, however, this indicates that proposed load balancer is at least as good as iptables DNAT.

[1] All of the nodes use a single interface for communication. At the load balancer node, the bandwidth for each direction of Full duplex Ethernet is consumed by the sum of request and response packets.

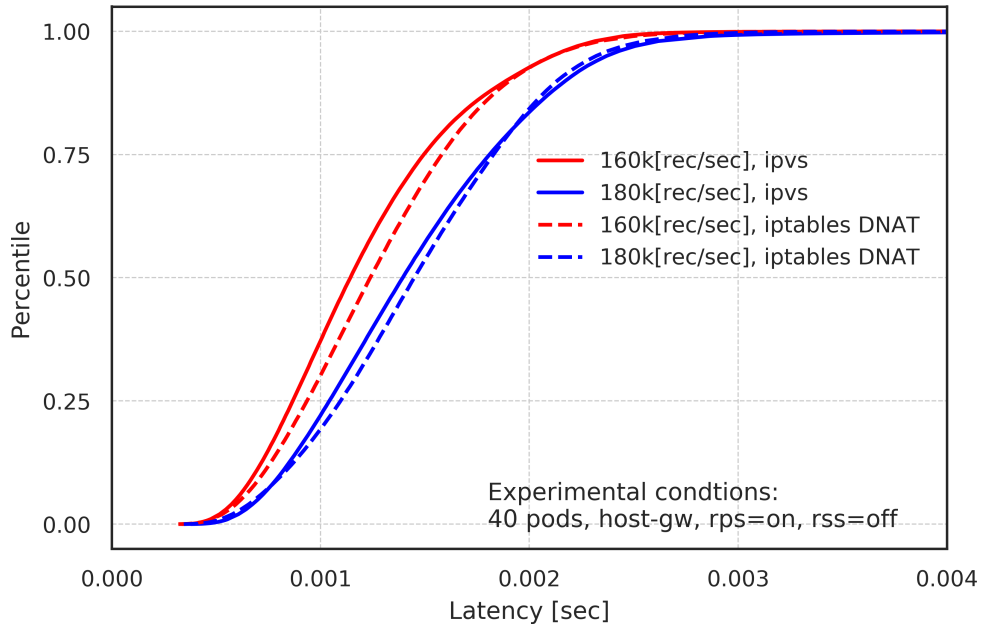


Figure 4.7: Latency for IPVS and iptables DNAT. Cumulative Distribution Function (CDF) of the latency for IPVS and iptables DNAT are compared, at the two constant loads, 160K[req/sec] and 180K[req/sec] . Smaller latencies are observed for IPVS.

L3DSR using IPVS-TUN

The performance levels of IPVS and iptables DNAT have been limited by 1 Gbps bandwidth at the load balancer node. This can be alleviated in the case of IPVS by using so-called Layer 3 Direct Server Return (L3DSR) setup. Figure 4.8 shows the schematic diagram illustrating the packet flow of the L3DSR experiment. The red arrows indicate the route HTTP request packets follow and the blue arrows indicate the route response packets follow. Since the response packets directly return to the client and do not consume the bandwidth at the load balancer node, the load balancer is expected to perform better.

The IPVS has a mode called IPVS-TUN. When the IPVS-TUN send out the packets to real servers, it encapsulates the original packet in ipip tunneling packet [35] that is destined to real servers. The real server receives the packet on a tunl0 device and decapsulates the ipip packet, revealing the original packet. Since the source IP address of the original packet is maintained, the returning packets are sent directly toward the benchmark client. In this scheme, the returning packets do not consume the bandwidth nor the CPU power of the load balancer node. Since iptables DNAT does not have the functions that enable L3DSR settings, this is one of the benefits only available for the proposed load balancer.

The author carried out throughput measurement using the experimental setup shown in Figure 4.8. Figure 4.9 compares the throughput of the IPVS-TUN, conventional IPVS and iptables DNAT. As can be seen in the figure, while the performance levels for IPVS and iptables DNAT exactly match because of the network bandwidth limitation, the performance level of IPVS-TUN is much higher than those. For example, the throughput of IPVS-TUN is about 1.5 times higher than those of conventional IPVS and iptables DNAT.

The saturated throughput indicates the maximum performance level of the load balancer, which is determined by network bandwidth at the benchmark client, or by CPU performance of either load balancer node or benchmark client. In the case of IPVS-TUN, it turned out that the maximum throughput is limited by the bandwidth at the benchmark client. Multipling the maxium throughput of about 290K [req/sec] with the response packet size 450[byte/req] (Appendix C) and 8 [bit/byte] results in 972M [bit/sec] .

The fact that the load balancer itself is not the performance limiting factor means that proposed load

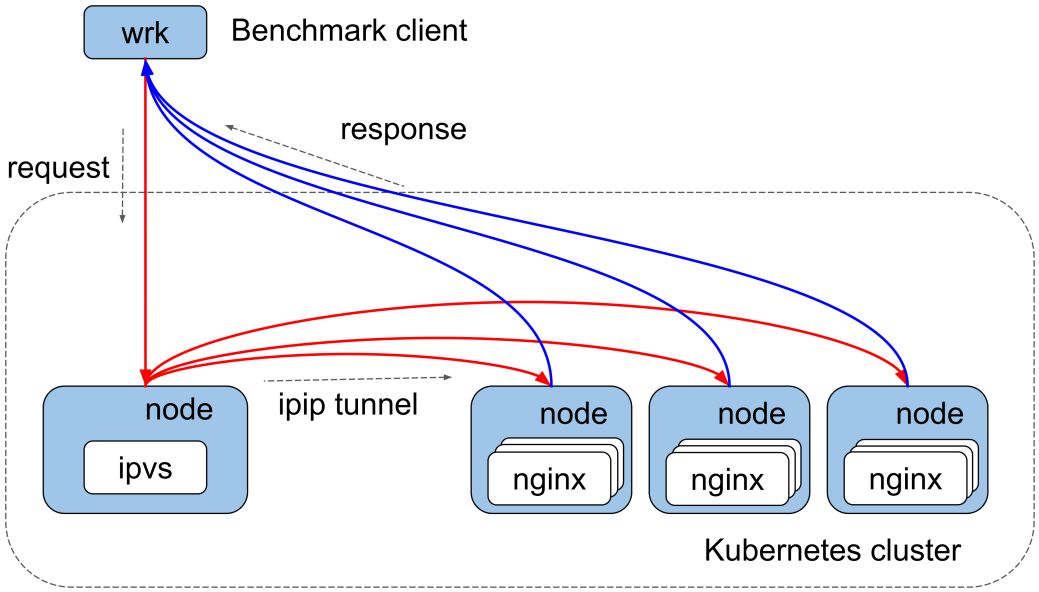


Figure 4.8: Experimental setup for L3DSR throughput measurement. The red arrows indicate the route HTTP request packets follow and the blue arrows indicate the route response packets follow. Since the response packets directly return to the client, the load balance is expected to perform better.

balancer has sufficient performance levels in 1 Gbps network.

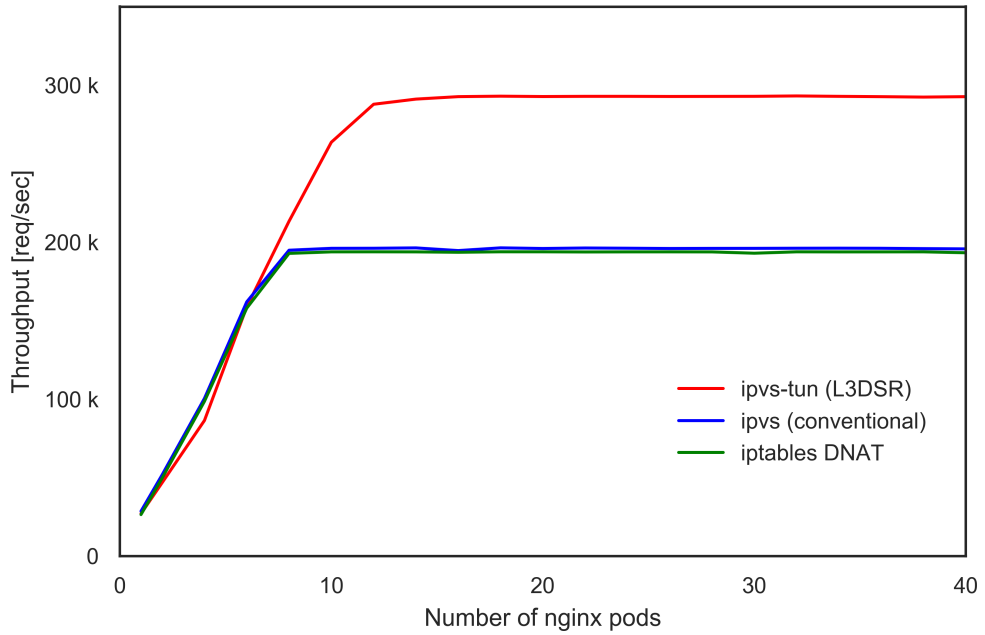


Figure 4.9: Throughput of L3DSR using IPVS-TUN. The throughput of IPVS-TUN is 1.5 times higher than those of conventional IPVS and iptables DNAT.

4.2 Cloud experiment

The throughput measurements were also carried out in GCP and AWS to show the containerized IPVS load balancer is runnable even in the cloud environment. The specifications of virtual machines used for the experiment in both environment are summarized in Table 4.3 and Table 4.4. In the cases of cloud environments, it is easy to change the machine specifications, especially CPU counts. Therefore, the author measured throughput with several conditions of them. In the case of GCP, custom instance with 32Gbyte memory and with 8, 16, and 32 CPU are used. And in the case of AWS instance type of c4.2xlarge, c4.4xlarge, and c4.8xlarge, which support single root I/O virtualization (SR-IOV), are used. The vxlan mode of the flannel is used for the overlay network in both of the cloud environment. As for multicore packet processing, different settings depending on the number of prepared queues for VMs are used. The setting "(RSS, RPS) = (on, off)" is used in GCP and the setting "(RSS, RPS) = (off, on)" is used in AWS.

Figure 4.10 and Figure 4.11 show throughput results that are measured in GCP and AWS, respectively. Both results show similar characteristics as the experiment in an on-premise data center in Figure 4.6, where throughput increased linearly to a certain saturation level that is determined by either network speed or machine specifications. It is also seen that the performance levels are higher for load balancer nodes with more CPUs in both GCP and AWS. These results indicate that the proposed IPVS load balancers function properly in GCP and AWS, and hence can be run in those environments.

In general, the throughput results in the cloud environments are inferior to those in the on-premise data center, even though much more powerful CPUs are used for VMs in the cloud environment than the experiment in the on-premise data center. For example, while the maximum throughput of the IPVS load balancer with eight physical cores was 190K[req/sec] in the on-premise data center (Figure 4.2), the maximum throughput in GCP and AWS are 160K[req/sec] and 100K[req/sec], respectively, even with 32 and 36 virtual CPUs. The author suspects that this is due to the inefficiency of the virtual machines as opposed to Bare Metal servers.

Although a detailed analysis is left for future work, the author confirmed that proposed load balancer

```
[GCP VM Specication for Client and Web Server Nodes ]
  Instance type: custom instance
  CPU: Xeon 2.2GHz, 16 cpus
  Memory: 16GB
  NIC: virtio_net /w 16 rx-queues
  (Node x 6, Client x 1)

[GCP VM Specication for Load balancer Node ]
  Instance type: custom instance
  CPU: Xeon 2.2GHz, 8, 16, 32 cpus
  Memory: 16GB
  NIC: virtio_net /w 8, 16, 32 rx-queues
  (Load balancer x 1)
```

Table 4.3: Virtual Machine specifications in GCP experiment. The author measured throughputs using load balancer nodes with 8 CPUs, 16 CPUs, and 32 cups. The number of rx-queues of each node was 8, 16 and 32, respectively. Since the same number of rx-queues as the number CPU is prepared, the setting with "(rss, rps) = (on, off)" is used.

```
[AWS VM Specication for Client and Web Server Nodes ]
  Instance type: m4.4xlarge
  CPU: Xeon E5-2686 v4 2.30GHz, 16 cpus
  Memory: 64GB
  NIC: ixgbevf /w 2 rx-queues
  (Node x 6, Client x 1)

[AWS VM Specication for Load balancer Node ]
  Instance type: c4.2xlarge, c4.4xlarge, c4.8xlarge
  CPU: Xeon E5-2666 v3 2.90GHz, 8, 16, 36 cpus
  Memory: 15GB, 30GB, 60GB
  NIC: ixgbevf /w 2 rx-queues
  (Load balancer x 1)
```

Table 4.4: Virtual Machine specifications in AWS experiment. The author measured throughputs using load balancer nodes with 8 CPUs, 16 CPUs, and 36 CPUs. Since there are only two rx-queues, the setting with "(rss, rps) = (off, on)" is used.

could run both in GCP and AWS.

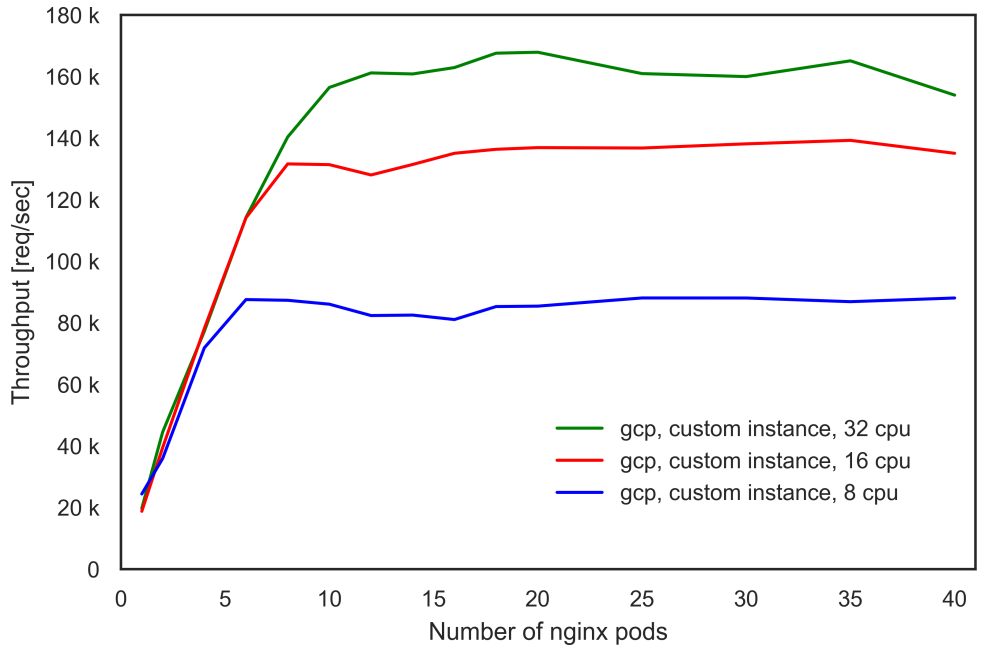


Figure 4.10: Throughput measurement results in GCP. The throughput increases linearly as the number of nginx *pod*s increases until it reaches the saturation level. The maximum throughput is higher for instances with more virtual CPUs.

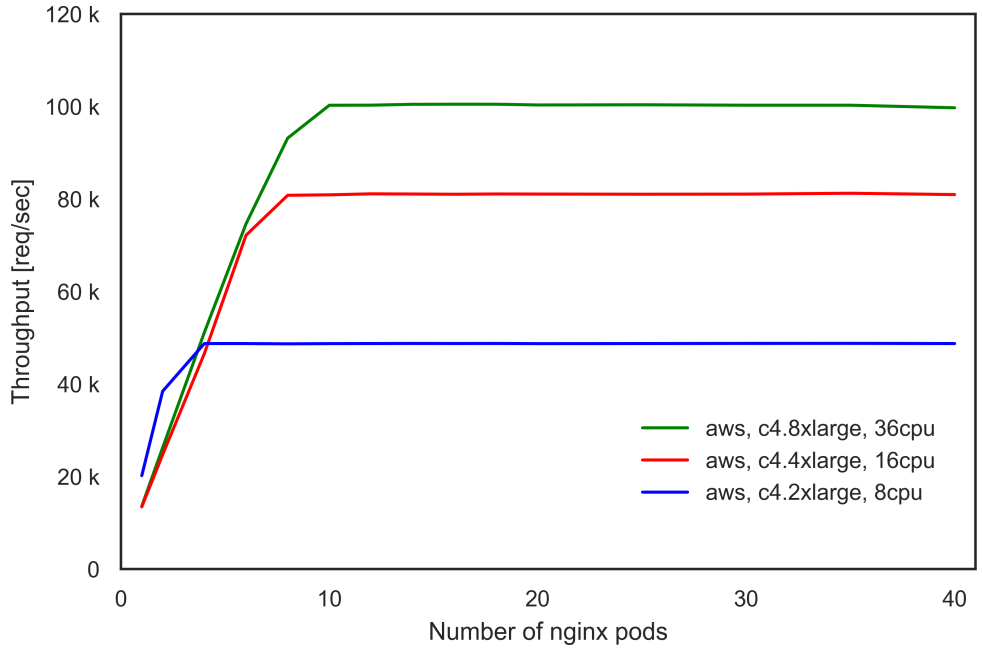


Figure 4.11: Throughput measurement results in AWS. The throughput increases linearly as the number of nginx *pod*s increases until it reaches the saturation level. The maximum throughput is higher for instances with more virtual CPUs.

4.3 Redundancy with ECMP

While containerizing IPVS makes it runnable in any environment, it is essential to discuss how to route the traffic to the IPVS container in a redundant and scalable manner. The ECMP technique is expected to make the load balancers redundant and scalable since all the load balancer containers act as active. The author examined the behavior of the ECMP routing table updates, by changing the number of the load balancers. After that, in order to explore the scalability, the author also measured the throughput from a benchmark client with ECMP routes when multiple of the IPVS container load balancers are deployed.

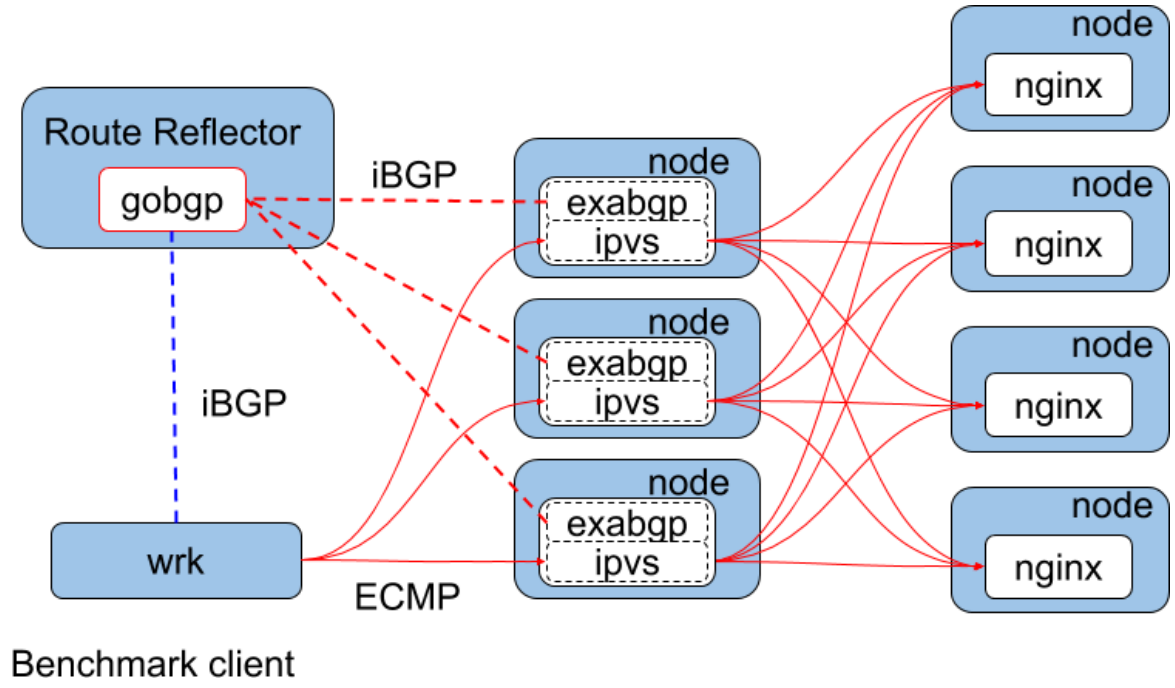


Figure 4.12: Benchmark setup for ECMP experiment. Each load balancer pods consists of both an IPVS container and an exabgp container. The routing table of the benchmark client is updated by BGP protocol through a route reflector.

Figure 4.12 shows the schematic diagram of the experimental setup. Table 4.5 summarizes hardware and software specifications. Notable differences from the previous throughput experiment in Figure 4.1 and Table 4.2 are as follows; 1) Each load balancer pods now consists of both an IPVS container and an exabgp container. 2) The routing table of the benchmark client is updated by BGP protocol through a route reflector. 3) The NIC of the benchmark client has been changed to 10 Gbps card, which prevented the bandwidth at the benchmark client from becoming the bottleneck too early. 4) Some of the software have been updated to the most recent versions at the time of the experiment.

```
[Hardware Specication]
  CPU: Xeon E5-2450 2.10GHz x 8 (with Hyper Threading)
  Memory: 32GB
  NIC: Broadcom BCM5720 with 4 rx-queues, 1 Gbps
  (Node x 6, Load Balancer x 4)
  CPU: Xeon E5-2450 2.10GHz x 8 (with Hyper Threading)
  Memory: 32GB
  NIC: Intel X550
  (Client x 1)

[Node Software]
  OS: Debian 9.5, linux-4.16.8
  Kubernetes v1.5.2
  flannel v0.7.0
  etcd version: 3.0.15

[Container Software]
  Keepalived: v1.3.2 (12/03,2016)
  nginx : 1.15.4 (web server)

[BGP Software]
  gobgp version 1.33 (route reector & benchmark client)
  exabgp 3.4.17 (load balancer)
```

Table 4.5: Hardware and software specifications for ECMP experiment. The NIC of the benchmark client is 10 Gbps card to measure the aggregated throughput of 1Gbps load balancers.

First, the author examined ECMP functionality by monitoring the routing table on the benchmark client. Table 4.6 (a) shows the routing table entry on the router when a single load balancer pod exists. From this entry, it is seen that packets toward 10.1.1.0/24 are forwarded to 10.0.0.106 where the load balancer pod is running. It also shows that this routing rule is updated by zebra. The routing table entry in Table 4.6 (b) is seen when the number of the load balancer pods is increased to three. There are three next hops towards 10.1.1.0/24, each of which is the node where the load balancer pods are running. The weights of the three next-hops are all 1. The update of the routing entry was almost instant as the author increased the number of the load balancers. Table 4.6 (c) shows the case where the author additionally started new service with two load balancer pods with service addresses in 10.1.2.0/24 range. It was possible to accommodate two services with different service IPs on the same group of nodes(10.0.0.105, 10.0.0.106, 10.0.0.107). The one has three load balancers and the other has two load balancers. The update of the routing entry was almost instant as the author started the load balancers for the second service.

As far as the route withdrawal is concerned, if an exabgp is killed by SIGKILL or SIGTERM the kernel of the node close the BGP connection by sending out a packet with FIN flag to the peer gobgpd on the route reflector, and thus the route is withdrawn immediately. The gobgp on the route reflector also periodically checks the BGP connection, and if the peer exabgp container is unresponsive for more than the specified duration, “hold-time “ setting in gobgpd, it will also terminate the connection and withdraw the route. The packets arriving within that duration will be dropped. However, it is possible to set up the “hold-time” short enough so that the retransmitted TCP packets from the client will be forwarded correctly to functioning load balancers.

```
10.1.1.0/24 via 10.0.0.106 dev eth0 proto zebra metric 20
```

(a) With single load balancer *pod*.

```
10.1.1.0/24 proto zebra metric 20
        nexthop via 10.0.0.105 dev eth0 weight 1
        nexthop via 10.0.0.106 dev eth0 weight 1
        nexthop via 10.0.0.107 dev eth0 weight 1
```

(b) With three load balancer *pod*s.

```
10.1.1.0/24 pro to zebra metric 20
        nexthop via 10.0.0.107 dev eth0 weight 1
        nexthop via 10.0.0.105 dev eth0 weight 1
        nexthop via 10.0.0.106 dev eth0 weight 1
10.1.2.0/24 proto zebra metric 20
        nexthop via 10.0.0.107 dev eth0 weight 1
        nexthop via 10.0.0.106 dev eth0 weight 1
```

(c) For a service with three load balancer *pod*s and a service with two load balancer *pod*s.

Table 4.6: ECMP routing tables. All the routing rules are updated by zebra. (a) According to this entry, packets toward 10.1.1.0/24 are forwarded to 10.0.0.106. (b) There is a routing rule with three next hops towards 10.1.1.0/24, each of which is the node where the load balancer pods are running. The weights of the three next-hops are all 1. (c) There are two routing rules regarding the services with different service IPs, one with three load balancers and the other with two load balancers. These load balancers share the same group of nodes, i.e., (10.0.0.105,10.0.0.106,10.0.0.107).

The author also carried out throughput measurement to show that the proposed architecture increases the throughput as the number of the load balancers is increased. Figure 4.13 shows the results of the measurements. There are four solid lines in the figure, each corresponding to the throughput result when there are one through four of the proposed load balancers. The saturated levels, i.e. performance levels depend on the number of the IPVS load balancer pods (lb x 1 being the case with one IPVS pods, and lb x2 being two of them and as such). The performance level increases linearly as the number of the load balancers increases up to four of the IPVS load balancers, indicating that the load balancer with the proposed architecture is scalable. The throughput of the load balancers does not scale further, because the benchmark program uses up CPU power of the benchmark client, i.e., the CPU usage is 100% when there are more than four load balancers. The author expects that replacing the benchmark client with more powerful machines, or changing the experimental setup so that multiple benchmark clients can simultaneously perform the throughput measurements, will improve the performance level further.

Figure 4.14 shows the throughput measurement results when the author periodically changed the number of the load balancers. The red line in the figure shows the number of IPVS load balancer pods, which is changed randomly every 60 seconds. The blue line corresponds to the resulting throughput. As can be seen from the figure, the blue line nicely follows the shape of the red line. This indicates that new load balancers are immediately utilized after they are created, and after removing some load balancers, the traffic to them is immediately directed to the existing load balancers.

Figure 4.15 shows a histogram of the ECMP update delay, where the author measured the delays until the number of running IPVS pods is reflected in the routing table on the benchmark client, as the number of the IPVS pods is changed randomly every 60 seconds for 20 hours. As can be seen from the figure, most of the delays are within 6 seconds, and the largest delay during the 20 hours experiment was 10 seconds.

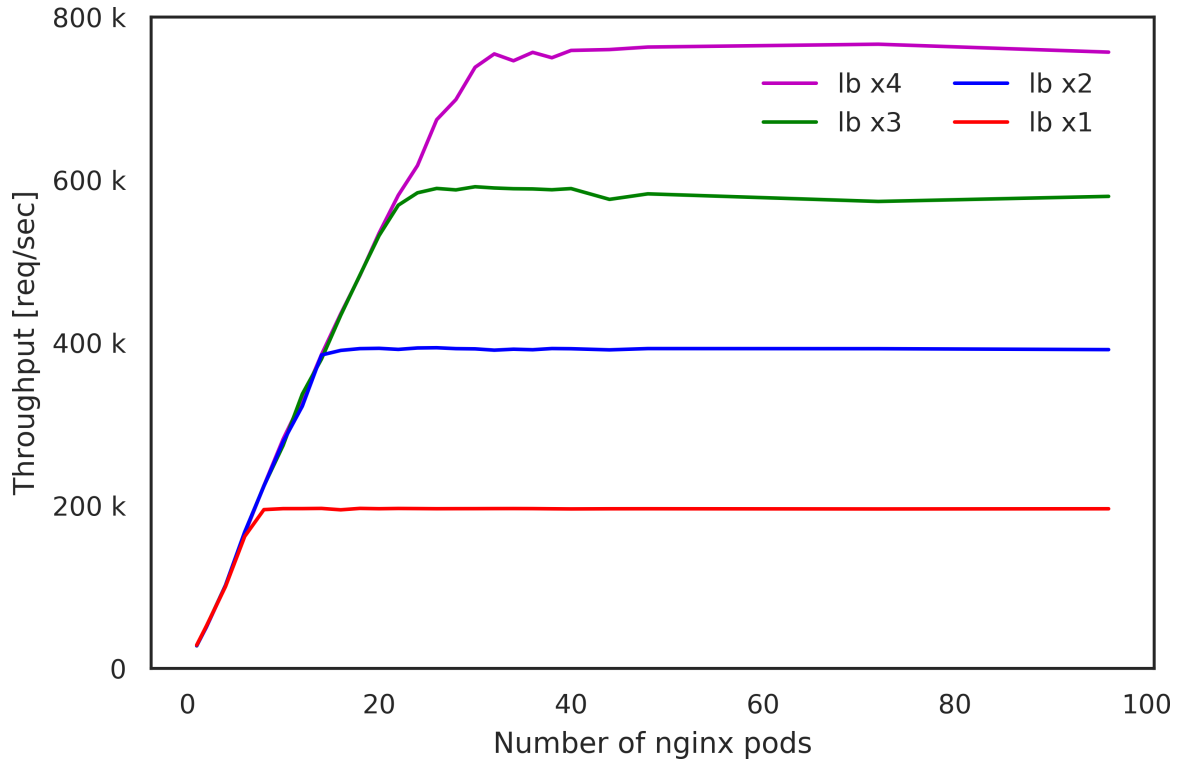


Figure 4.13: Throughput of ECMP redundant load balancer. The throughputs are measured for a single load balancer (lb x1), two (lb x2), three (lb x3) and four (lb x4) load balancers.

This is practically quick enough because normally resizing of the load balancer cluster does not occur so often and from the viewpoint of a client, 6 seconds is within a duration of tree TCP retransmissions [50].

The author concludes that the proposed redandancy architecture for the load balancer functions properly and the ECMP routing update is quick enough.

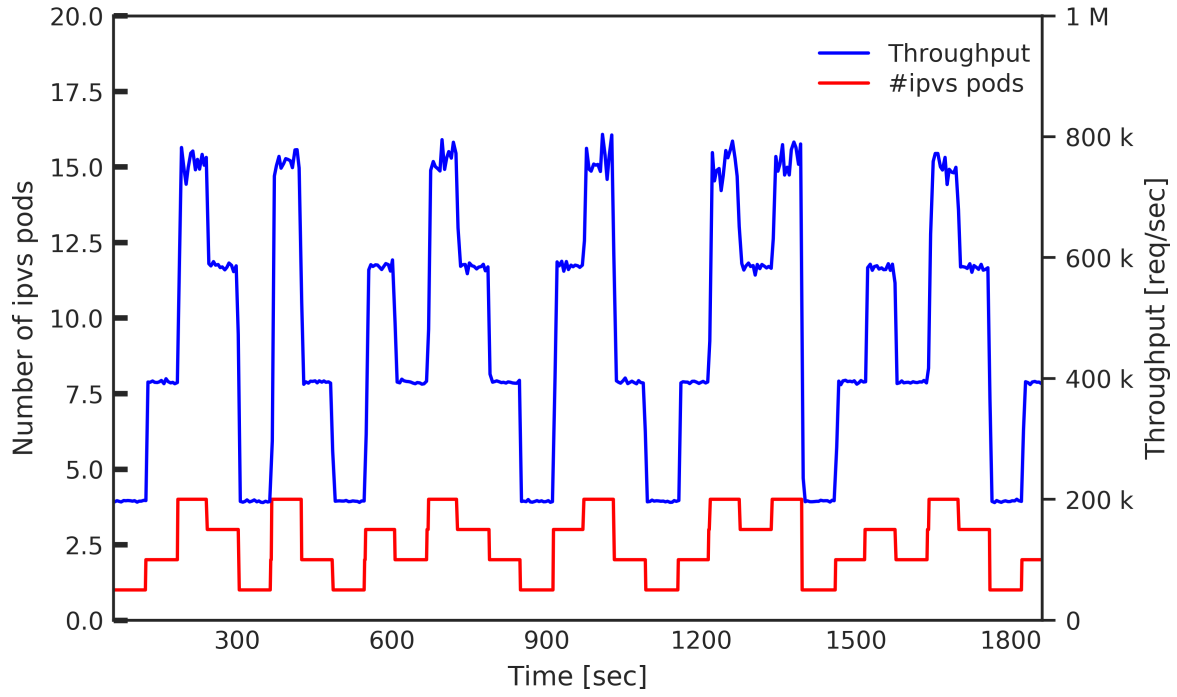


Figure 4.14: Throughput responsiveness. Throughput responsiveness when the number of load balancers is changed randomly in every 60 seconds is shown.

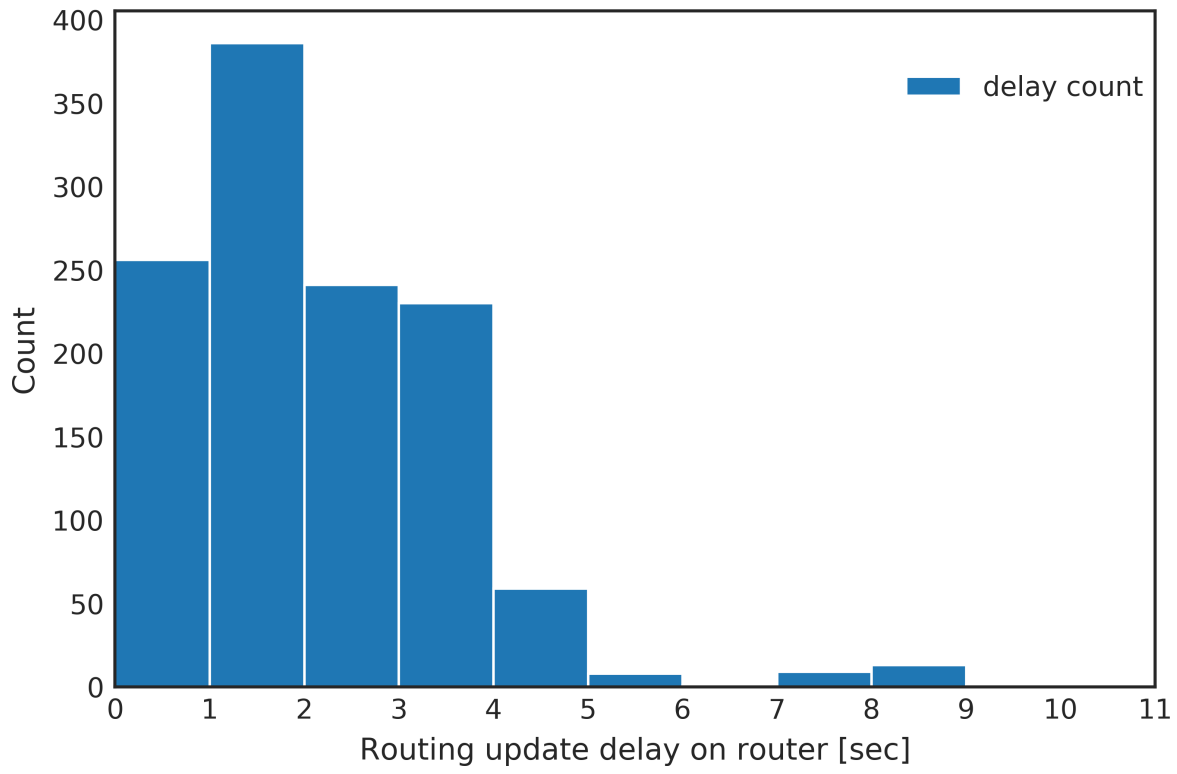


Figure 4.15: ECMP update delay histogram. This shows the delays until the number of running IPVS pods is reflected in the routing table on the benchmark client, when the number of the IPVS pods is changed randomly every 60 seconds for 20 hours.

4.4 Summary

In this chapter, the author evaluated the feasibility of the proposed load balancer. The author carried out throughput measurement of the load balancer and verified the followings; (1) Portability: In the on-premise data center, the throughput of the proposed load balancer linearly increases as the number of nginx *pod*s increases, and then it eventually saturates, indicating the load balancer functions properly. This characteristic is also seen in the experiment in GCP and AWS, also indicating that the proposed load balancer properly functions in these environments. (2) Redundancy and scalability: The ECMP routing update in the proposed architecture is properly functioning and quick enough. The linear scalability of the ECMP throughput has been confirmed up to 4x of single load balancer throughput. (3) Performance: The throughput of the load balancers are limited by the network bandwidth in the 1 Gbps environment. In the case of the IPVS and the iptables DNAT, maximum throughputs are the same, because they are limited by network bandwidth at load balancer node. In the case of the IPVS-TUN (L3DSR), the maximum throughput is limited by network bandwidth at the benchmark client, and about 1.5 times larger than those of the IPVS and the iptables DNAT. The fact that the load balancer itself is not the performance limiting factor means that proposed load balancer has sufficient performance levels in 1 Gbps network. From these results, the author concludes that the proposed load balancer is portable, redundant and scalable while providing sufficient performance levels in 1Gbps network environment.

Chapter 5

Perfomance in faster network

In the previous chapter, the author evaluated the feasibility of the proposed load balancer in 1Gbps network. The author verified that the proposed load balancer has sufficient throughput in 1 Gbps network. In this chapter, the author shows that the proposed load balancer has sufficient throughput in 10Gbps network. The author also discusses how to improve the performance levels in faster networks, e.g., 100 Gbps and finds that there are rooms for improvements in both the container network and the software load balancer itself. Although these should be explored further in the future work, the author presents preliminary experimental results of a novel software load balancer using eXpress Data Plane (XDP) technology.

5.1 Throughput measurement in 10G network

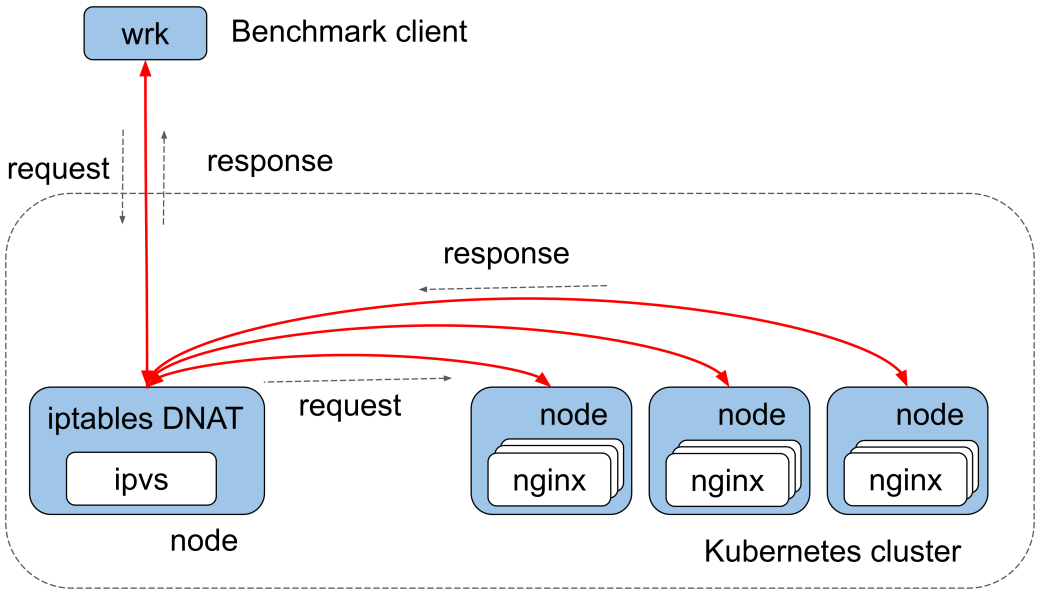
In order to evaluate the performance levels of the proposed load balancer in a 10 Gbps network environment, the author carried out throughput measurements. Table 5.1 summarizes the hardware and software specification used in the experiment. Bare metal servers with Intel X550 network card was used. The X550 NIC has a maximum of 64 rx-queues, and 16 of them are activated by the driver at the boot time since there are 16 logical CPUs. The setting " (RSS, RPS)=(on, off)" is used because interrupts from each of 16 rx-queues can be assigned to separate logical cores. As a result, packet processing is distributed to all of the 16 logical cores, which results in the best performance in most of the cases. The host-gw mode is used as the backend mode of the flannel overlay network.

```
[Hardware Specication]
  CPU: Xeon E5-2450 2.10GHz x 8 (with Hyper Threading)
  Memory: 32GB
  NIC: Intel X550 with 64 rx-queues (16 activated), 10 Gbps
  (Node x 6, Load Balancer x 1, Client x 1))

[Node Software]
  OS: Debian 9.5, linux-4.16.8
  Kubernetes v1.5.2
  flannel v0.7.0
  etcd version: 3.0.15

[Container Software]
  Keepalived: v1.3.2 (12/03,2016)
  nginx : 1.15.4 (web server)
```

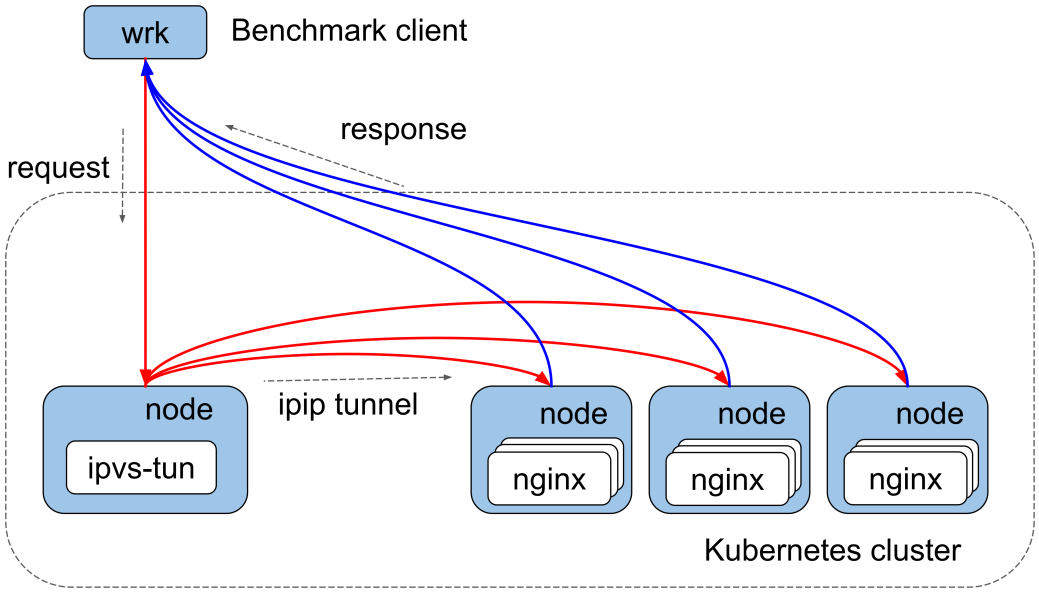
Table 5.1: Hardware and software specifications for 10 Gbps experiment. There are 16 rx-queues activated for the NIC, to match the number of logical CPUs.

Figure 5.1 show experimental setups for the throughput measurements. Multiple nginx *pods* are deployed on multiple nodes as web servers in the Kubernetes cluster. In each nginx *pod*, single nginx web server program that returns the IP address of the *pod* itself is running. The author then launched IPVS and IPVS-TUN pod as load balancers on one of the nodes, after that, the author performed the throughput measurement

changing the number of the nginx web server pods. On every Kubernetes node, there are iptables DNAT rules that function as an internal load balancer. The author also measured throughput of the iptables DNAT as a load balancer. The throughput is measured by sending out HTTP requests from the wrk towards a load balancer and by counting the number of responses the benchmark client received. In the case of the IPVS-TUN, i.e., the tunneling mode of IPVS, the response packets follow the different route than the case of conventional IPVS and iptables DNAT. As a result, the better performance level is expected for IPVS-TUN since the load balancer node only has to deal with request packets of the traffic.



((a))



((b))

Figure 5.1: Benchmark setups in 10 Gbps experiment. (a) The setup used in throughput measurements of IPVS and iptables DNAT. The request and response packets both go through the load balancer node. (b) The setup used in throughput measurements of IPVS-TUN. The response packets for IPVS-TUN, return directly to the benchmark client.

Figure 5.2 shows the throughput results of IPVS, IPVS-TUN and iptables DNAT in 10 Gbps environment. The general characteristics of a load balancer, where the throughput increases linearly to a saturation level as the number of nginx container increases, can be seen. The maximum throughput of each load balancer is limited by either packet forwarding efficiency of the software load balancer itself or the bandwidth of the network. The maximum throughput level of the iptables DNAT is close to 780k [req/sec], where the CPU usage of the benchmark client was 100%. The maximum throughput levels of IPVS and IPVS-TUN are less than that of iptables DNAT.

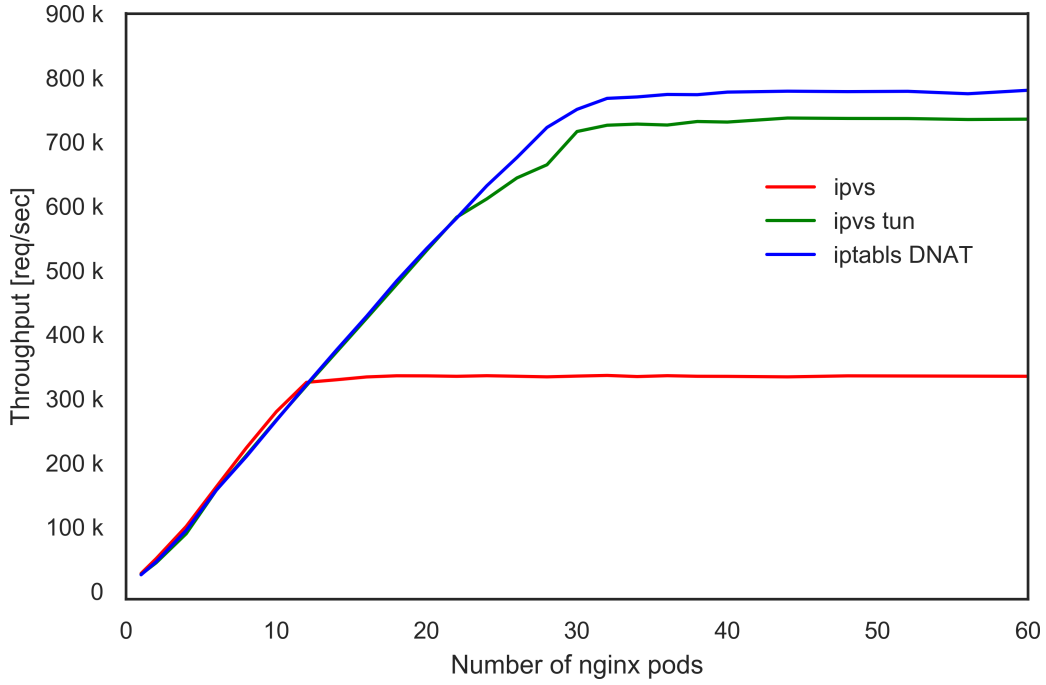


Figure 5.2: Throughput of load balancers in 10 Gbps. The iptables DNAT rules exist in the node net namespace. The IPVS and IPVS-TUN are in containers. The throughput of the iptables DNAT is the highest.

Figure 5.2 shows comparison of CPU usage between load balancers. CPU usages are sampled on the load balancer nodes at the time of the throughput measurement using a program called dstat [51]. It is seen that IPVS-TUN uses less CPU resource than IPVS because the load balancer node does not have to deal with the response packets. The iptables DNAT uses even less CPU resource than IPVS and IPVS-TUN. Possible reasons for the lesser performance levels for IPVS are as follows; (1) It is possible that the IPVS and IPVS-TUN program themselves are less efficient than iptables DNAT. (2) The network setup for the container, i.e., bridge+veth may be causing the overhead. While iptables DNAT rules exist in node net namespace, proposed IPVS and IPVS-TUN exist in container net namespace. In order to clarify which of these is the true reason for the performance difference, the author carried out throughput measurement for IPVS and IPVS-TUN without using the container network, i.e., in node net namespaces.

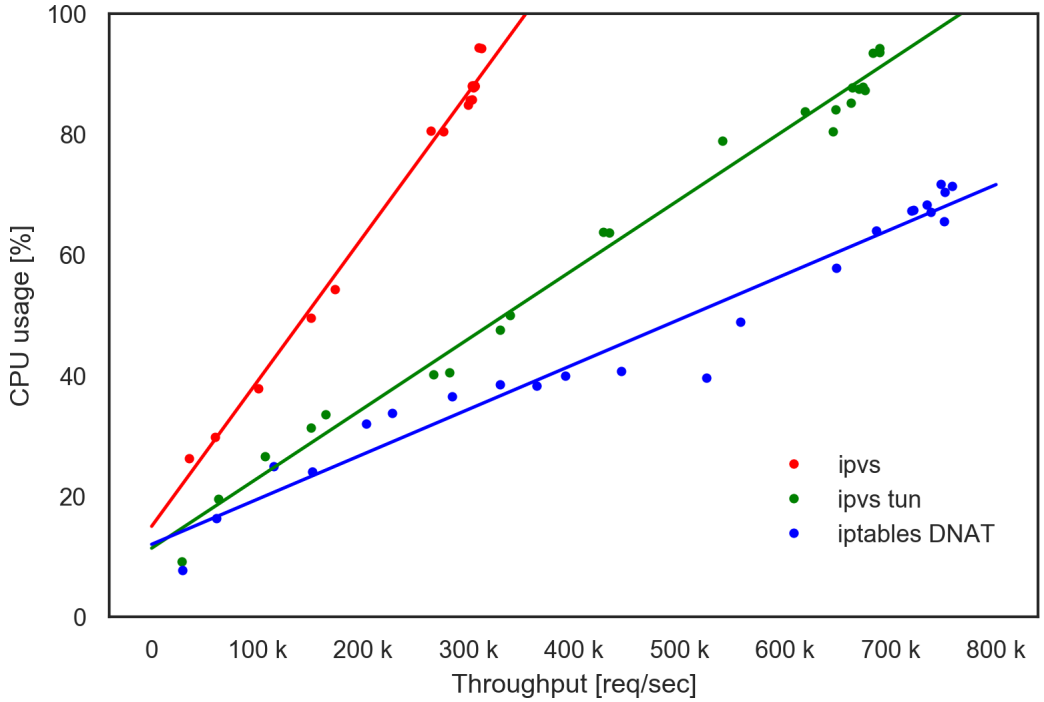


Figure 5.3: CPU usage of load balancers in containers. The iptables DNAT rules exist in the node net namespace. The IPVS and IPVS-TUN are in containers. The iptables DNAT consumes the smallest amount of the CPU resource.

Performance comparison in node net namespace

The IPVS and IPVS-TUN load balancers were setup on one of the nodes. The load balancing rules were created in the node namespaces, and then throughput measurement were carried out.

Figure 5.4 shows the throughput of IPVS and IPVS-TUN in the node net namespace together with the throughput of the iptables DNAT. The throughputs of the IPVS and IPVS-TUN are improved from the previous results in Figure 5.2. This improvement indicates that the overhead due to container network using veth+bridge has a significant impact. The throughput of the IPVS-TUN is almost identical to that of iptables DNAT.

The maximum throughput of these are probably limited by the performance of the benchmark client since the CPU usages of the benchmark client at the saturation level were almost 100% in both cases.

Figure 5.5 shows CPU usages of each load balancers. The CPU usage of the IPVS-TUN is smaller than that of IPVS. This is because the load balancer does not process the response packets in L3DSR setting. The CPU usage of the IPVS is still more extensive than that of iptables DNAT, indicating that IPVS is inherently less efficient than iptables DNAT.

The author summarizes this section as follows; The IPVS itself is less efficient than iptables DNAT. Using the container network, i.e., veth+bridge further degrades the throughput of IPVS.

Therefore, both of these are the reasons for inferior performance levels for IPVS and IPVS-TUN in containers.

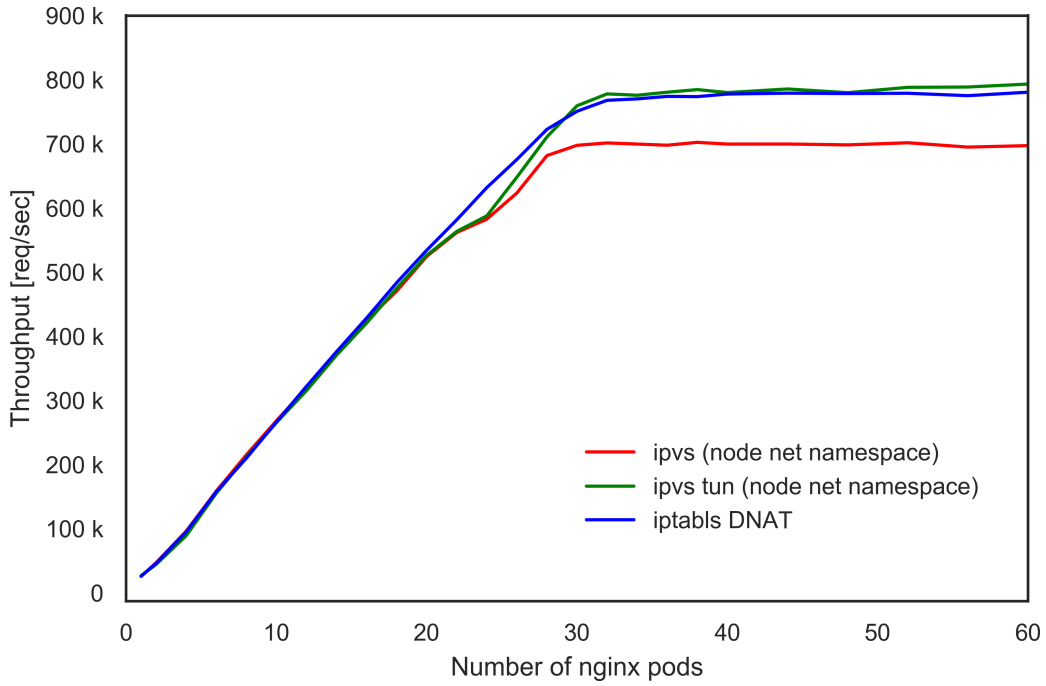


Figure 5.4: Throughput of load balancers in node namespace. The performance levels of the IPVS and IPVS-TUN are greatly improved from those in Figure 5.2 by placing them in node net namespace.

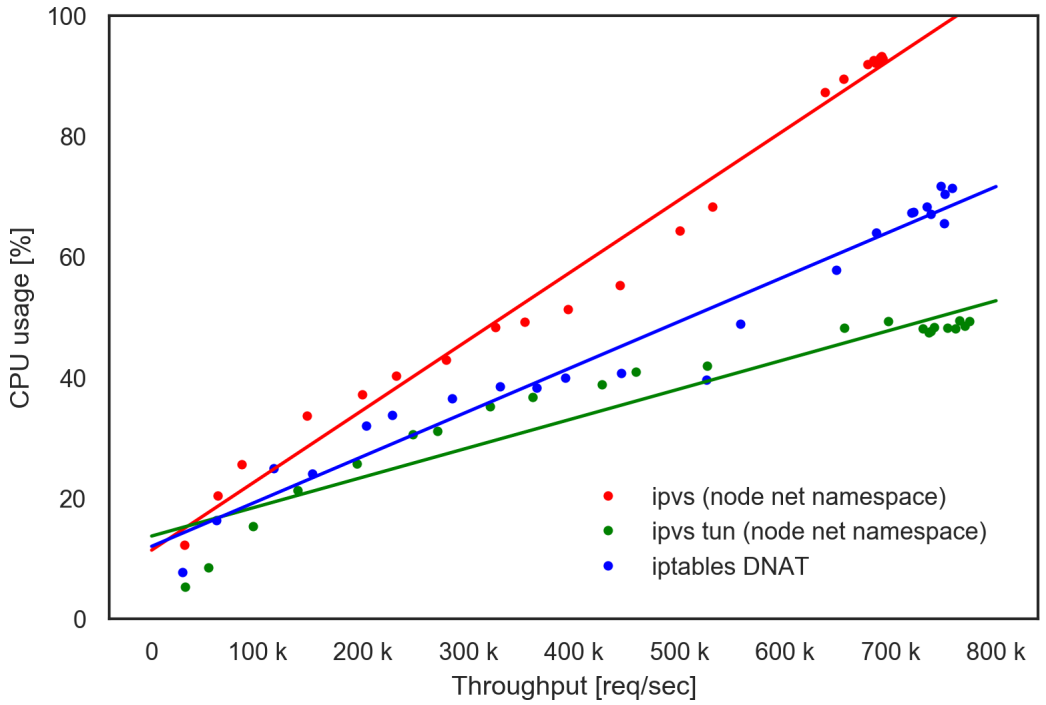


Figure 5.5: CPU usage of load balancers on nodes. CPU usages of IPVS and IPVS-TUN greatly improved from those in Figure 5.3 by placing them in node net namespace. While the IPVS-TUN consumes the smallest amount of the CPU resource, the CPU usage of IPVS is still larger than that of iptables DNAT.

5.2 Discussion of required throughput

The author has compared the performance of proposed load balancers in 10 Gbps in the previous section. Although the proposed load balancer may not be the most efficient one, herein, the author shows that it has sufficient throughput for 10 Gbps network environment.

Table 5.2 summarizes the maximum throughputs of the different load balancers obtained in the experiments so far. Depending on the experimental conditions different part of the experimental setup limits the throughput of the load balancers. Since the performance bottlenecks are mainly due to network bandwidth in 1 Gbps network, it is easy to estimate the possible bottleneck due to bandwidth in a faster network. Since benchmark client exists at the location where normally the upstream router exists, the performance bottleneck at the benchmark client corresponds to the maximum throughput that the load balancer should handle.

For example, the bottleneck at the benchmark client is about 293K [req/sec] in the 1 Gbps network. The load balancers only need to be able to handle at most 293K [req/sec] equivalent of the traffic. Even if the load balancer is capable of handling 500K [req/sec], the throughput of the system is ultimately determined by the bottleneck at the entrance, that is 293K [req/sec]. The maximum throughput in 1 Gbps, i.e., 293K [req/seq] is already achieved by single IPVS-TUN (293K [req/seq]) or two of IPVS load balancers (193K x 2 [req/seq]) with ECMP redundancy.

In the case of 10 Gbps network, the maximum throughput determined by the bottleneck at the entrance is 2.9M [req/sec].

Single IPVS-TUN cannnot handle this much of the traffic.

However, this is still achievable without much of the hassle by using four of IPVS-TUN (731K x 4 [req/seq]) or nine of IPVS load balancers (335K x 9 [req/seq]) with ECMP redundancy.

In the case of 100 Gbps network, where the load balancers are required to handle up to 29M [req/sec] of the throughput, the inefficiency of the software load balancer in a container can become a real problem. Because in order to handle 29M [req/sec] of the traffic, 90 of IPVS load balancer would be needed. In this case, more efficient load balancer or container network is needed. In the next section, the author tries to improve the efficiency of a load balancer, by implementing novel XDP load balancer. Except for such cases, the proposed load balancer can provide sufficient throughput.

Type	namespace	Throughput [req/sec]	Bottleneck
iptables DNAT	node	193K	Bandwidth filled with request + response @ load balancer
IPVS	container	197K	Bandwidth filled with request + response @ load balancer
IPVS-TUN	container	293K	Bandwidth filled with response @ benchmark client

(a) 1 Gbps experiment

Type	namespace	Throughput [req/sec]	Bottleneck
iptables DNAT	node	778K	CPU~100% @ benchmark client
IPVS	container	335K	CPU~100% @ load balancer node
IPVS-TUN	container	731K	CPU~100% @ load balancer node
IPVS	node	700K	CPU~100% @ load balancer node
IPVS-TUN	node	780K	CPU~100% @ benchmark client

(b) 10 Gbps experiment

Table 5.2: Summary of the maximum throughputs.

5.3 XDP load balancer

The eXpress Data Path (XDP) [38] is Linux kernel technology recently developed, where the tools and functionality to intercept and process the packets in the earliest phase as possible are provided. By using XDP, one can write packet manipulation code using a subset of the C programing language, byte-compile it, and hook it into the place before the socket buffer is assigned, thereby speeding up network manipulation. Typical applications include packet drop against DDOS attack, simple packet forwarding, and load balancing. One of the benefits of the XDP compared to the technology using Data Plane Development Kit (DPDK) [39] is that in the case of XDP, the packets that do not match the rule for processing are then passed to normal Linux kernel's network stack. Therefore there is no need for preparing dedicated NIC for fast and efficient network processing. The author implemented the XDP load balancer and carried out throughput measurement.

Implementation

Figure 5.6 show schematic diagram of the XDP load balancer, xlb, which is implemented by the author. The xlb consists of programs and configurations shown in Table 5.3. The xlb_kernel.ll is the byte-compiled eBPF program that actually process the packets based on the load balance rules in the xlb table. Load balancing rules are populated by a userspace daemon xlbd from the configration file xlbd.conf and nexthop and MAC address information obtained from the Linux kernel.

Throughput results

The author carried out the throughput measurement for the XDP load balancer, xlb. The hardware and software configurations are same as the ones in Table 5.1. The experimental setup is also same as the one in Figure 5.1(b). Since current implementation of xlb does not support multi core packet processing, the setting "(RSS,RPS)=(off,off)" is used in the throughput measurement. All the interrupt from the NIC are notified to a single core.

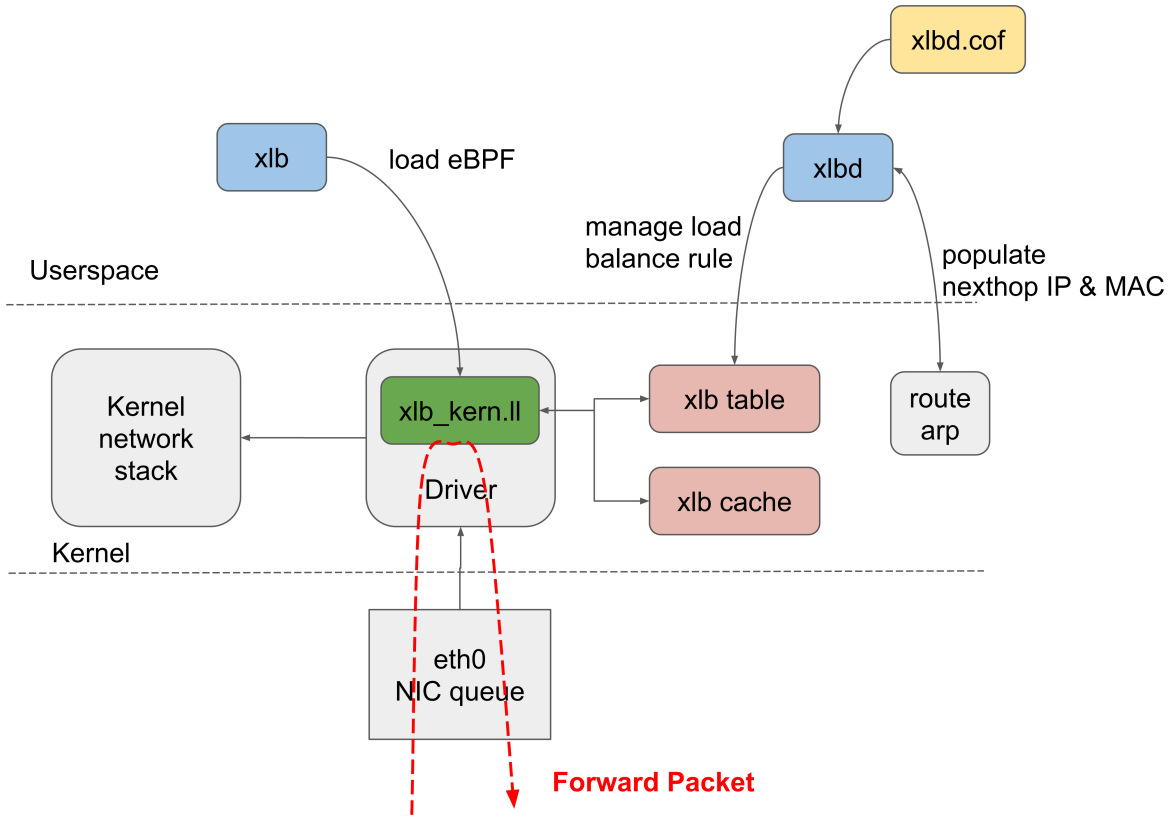


Figure 5.6: Xlb architecture. The author implemented an XDP load balancer named xlb.

Name	Function
xlb_kern.ll	byte compiled eBPF program
xlb	utility to inject eBPF program into kernl
xlbd	daemon to control load balance table
xlbd.conf	load balancing configuration
xlb table	load balance table
xlb cache	load balance cache

Table 5.3: Xlb components.

Figure 5.8 compares the throughput of xlb and iptables DNAT. Although a single core is used for the packet processing, the throughput of the xlb load balancer is 390k[req/sec], which is close to half of the iptables DNAT's throughput with 16 core (eight physical cores) packet processing. Figure5.8 compares CPU usages between xlb and iptables DNAT. At a given throughput the xlb consumes much less CPU resource than iptables DNAT. These results indicate that load balancer using XDP technology is very promising.

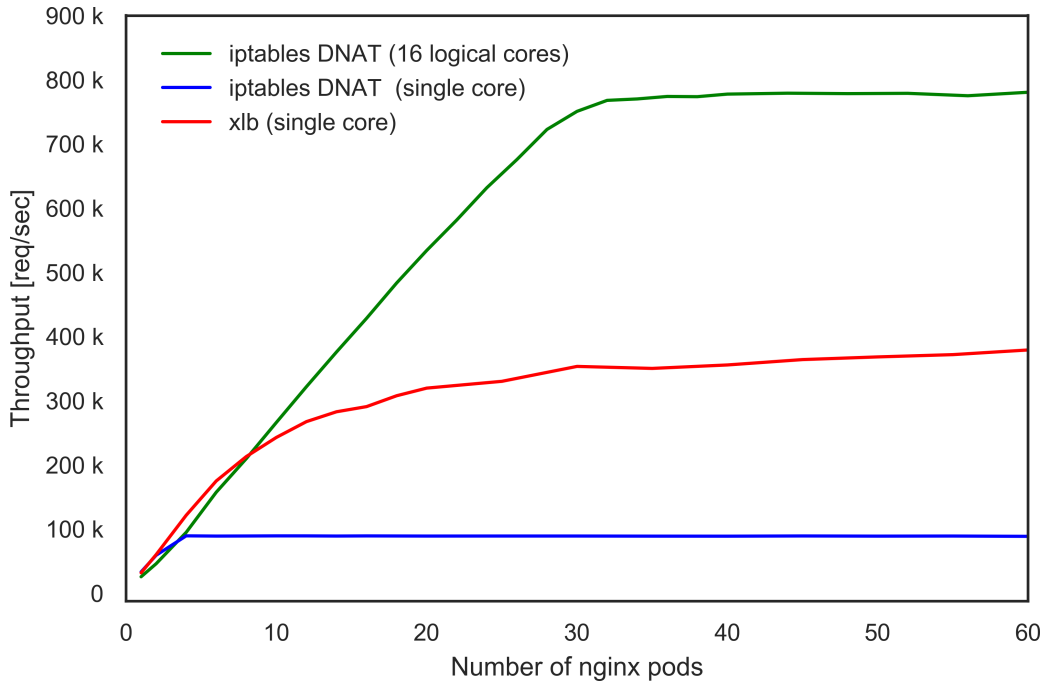


Figure 5.7: Throughput of xlb load balancer. The xlb load balancer is placed in node net namespace. The setting "(RSS,RPS)=(off,off)", i.e., single core packet processing is used for the xlb measurement. The results of iptables DNAT for "(RSS,RPS)=(on,off)" and "(RSS,RPS)=(off,off)" are also shown for comparison. The throughput of the xlb is much higher than that of iptables DNAT with single core packet processing. Although using only a single core, the throughput of the xlb load balancer is close to half of the iptables DNAT's with 16 core (eight physical core) packet processing.

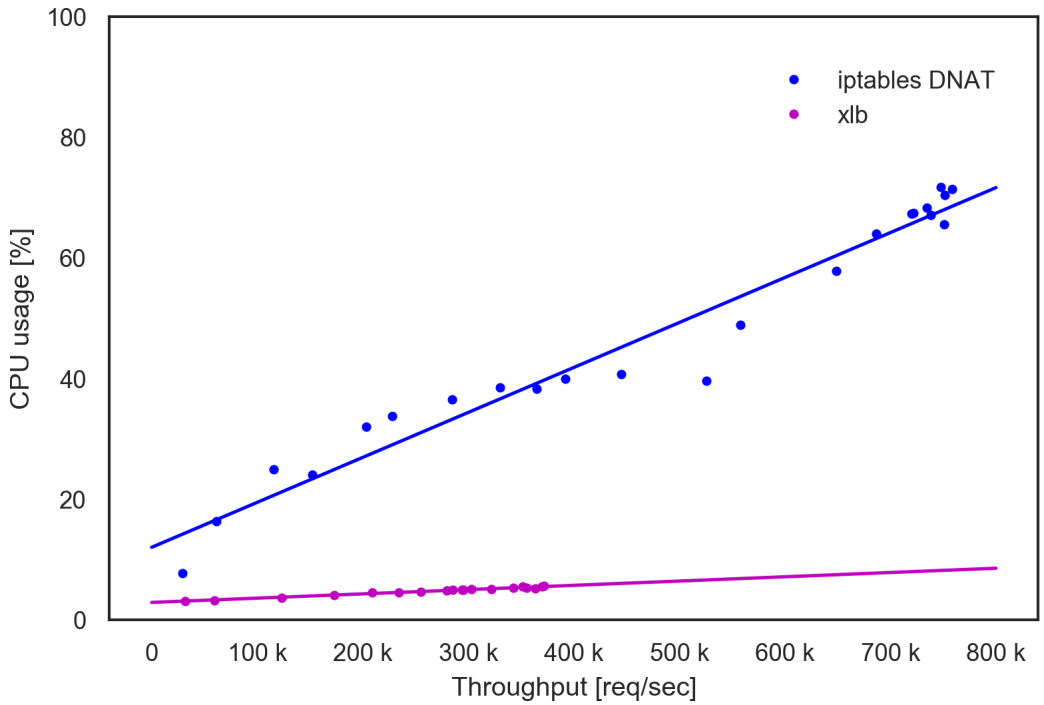


Figure 5.8: CPU usage of xlb load balancer. The xlb uses much less CPU resource than iptables DNAT.

5.4 Summary

In this chapter, the author has shown that the proposed load balancer has sufficient throughput in 10 Gbps network. The maximum throughput for IPVS-TUN is 731K [req/sec], which is sufficient because four of the load balancers with ECMP setup can deal with maximum traffic of 2.9M [req/sec] in 10 Gbps network.

The author also discussed how to improve the performance levels for faster networks. The throughputs of IPVS and IPVS-TUN in node net namespace are significantly improved from those in container net namespace. This indicates that there is unignorable overhead due to container network using veth+bridge. The CPU usage of the IPVS in node net namespace is more extensive than that of iptables DNAT, indicating that IPVS is inherently less efficient than iptables DNAT. The author considers that both of these should be improved in future work.

As an effort to improve the efficiency of the software load balancer,

the author has implemented a software load balancer, xlb, using XDP technology, and presented the preliminary experimental result. The obtained throughput 390K [req/sec] with single core packet processing is very promising. The author estimates that about five of the software load balancer using this technology with 16 core packet processing can provide sufficient throughput, 29M [req/sec] in 100 Gbps environments in the future.

From these results, the author concludes this chapter as follows; 1) The proposed load balancer has sufficient performance levels in 10 Gbps network environment. 2) For a faster network, e.g., 100 Gbps, improvement in container network and in software load balancer itself is needed, which should be explored in future work. 3) The author implemented a software load balancer using XDP technology, and the preliminary result has shown that this technology is very promising.

Chapter 6

Related Work

In this chapter, the author presents the related work of this study. The purpose of this study has been to improve the portability of web applications by using container orchestrators as a common middleware. Doing so will give users the freedom to migrate their services when there is a disaster, expand their businesses, and prevent vendor lock-ins, etc.

However, none of the existing orchestrators has a standard method to fully automate the setup of routes for ingress traffic from the Internet, regardless of different type of infrastructures. As as a result, they fail to provide the standard interfaces to web applications.

Therefore, the author proposes a cluster of software load balancer containers for Kubernetes, which can be used in different infrastructures.

Following this logic, here the author presents related work regarding the following subjects: (1) Portability of web applications.

(2) Software load balancers for Kubernetes.

In addition to these, there are several software load balancers for cloud environments. The author presents related work regarding (3) Cloud load balancers.

Cloud providers have developed cloud load balancers, aiming to differentiate their cloud infrastructure by seeking the best performances, while the author aims to provide a portable load balancer common to any infrastructure by using standard OSS technologies.

Despite the difference in purposes, it is worthwhile comparing the technology components in order to assess if the proposed load balancer is state of the art.

6.1 Portability of web applications

Portability: There have been numerous works that identify importance of interoperability, portability and avoiding vendor lock-in issues in cloud computing [52, 53, 1, 54, 55, 55, 56].

There are good reviews about this subject [55, 2]. According to one of the articles the vendor lock-in problem is a direct consequence of the lack of interoperability and portability.

Opara-Martins et al. [1] conducted a survey of 114 participants and argue from a business perspective that "vendor lock-in is a major barrier to the adaption of cloud computing, due to the lack of standardization."

As for solutions for the portability issues, some suggest migration of VM or container [57, 58] to different locations.

The others suggest Meta Cloud [59] and federations [60].

Federations use multiple clouds infrastructures in a coordinated way. Federations can also be called multi-cloud or inter-cloud. The following Kubernetes based federations also use multiple data centers or cloud infrastructures in a coordinated way, where Kubernetes controls each of the data centers and acts as a common middleware.

Kubernetes federation: Kubernetes developers are trying to add federation [60] capability for handling situations where multiple Kubernetes clusters [1] are deployed on multiple cloud providers or on-premise data centers. Those Kubernetes clusters are managed by the Kubernetes federation API server (federation-apiserver). According to their explanation[60], the federation capability provides the followings:

> " High Availability: By spreading load across clusters and auto configuring DNS servers and load balancers, federation minimizes the impact of cluster failure. Avoiding provider lock-in: By making it easier to migrate applications across clusters, federation prevents cluster provider lock-in. "

The approach taken in Kubernetes federation aligns with this thesis.

However, how each Kubernetes cluster is run on different types of cloud providers and/or on-premise data centers, especially when the load balancers of such environments are not supported by Kubernetes, seems beyond the scope of that project. This thesis is mainly focused on how to provide a common load balancer to different types of infrastructures.

There are other works [61, 62] regarding Kubernetes federation.

Kim et.al. [61] federate multiple Kubernetes clusters in the different cloud regions using TOSCA [63, 64] based approach. Goethals et.al.[62] connects different data centers using OpenVPN [65] and deploy Kubernetes cluster in virtual data center that span across multiple locations. These justify that there are needs to commonize varying cloud infrastructures and data centers using Kubernetes as a common middleware. This thesis differs in that it is more focused on the load balancer features that are overlooked in the cloud portability context.

6.2 Software load balancers for Kubernetes

In this study the author proposed a container cluster architecture and verified its feasibility using Kubernetes as an example. The author proposed a cluster of software load balancer using IPVS in container. Other groups also have proposed software load balancers for Kubernetes.

First, Kubernetes comes with proxy daemon that setup iptables DNAT based internal load balancer on every node[2].

Once the ingress traffic reaches one of the nodes, the packets are directed to existing *pods*. In conventional setup, the traffic is manually routed to one of the nodes, which lacks the redundancy and scalability. In cloud environments where there is supported load balancers, Kubernetes has a feature to automatically setup the cloud load balancer, so that the traffic is distributed all of the existing nodes.

Nginx-ingress[67, 68] utilizes the ingress[46] capability of Kubernetes,to implement a containerized Nginx proxy as a load balancer. Nginx itself is famous as a high-performance web server program that also has the functionality of a Layer-7 load balancer. Nginx is capable of handling Transport Layer Security(TLS) encryption, as well as Uniform Resource Identifier(URI) based switching. However, the flip side of Nginx is that it is slower than Layer-4 switching.

The kube-keepalived-vip[69] project is trying to use Linux kernel's ipvs[20] load balancer capabilities by containerizing the keepalived[70]. The kernel ipvs function is set up in the host OS's net namespaces and is shared among multiple web services, as a part of the Kubernetes cluster infrastructure. Our approach differs in that the ipvs rules are set up in container's net namespaces and function as a part of the web service container

[1] The *Kubernetes cluster* refers to a server cluster controlled by the Kubernetes container management system, in this thesis.

[2] Until the author published the paper [66] regarding this thesis, the internal load balancer only used iptables DNAT. Latest release of the Kubernetes offers the internal load balancer using IPVS.

cluster itself. The load balancers are configurable one by one, and are movable with the cluster once the migration is needed. The kube-keepalived-vip's approach lacks flexibility and portability whereas ours provide them.

MetalLB [71] is a load-balancer implementation for bare metal Kubernetes clusters, using standard routing protocols. It has two operating modes, layer 2 mode, and BGP mode. In the layer 2 mode, one of the nodes is chosen as a leader and the leader sends out gratuitous ARP (ipv4) or NDP (ipv6) packets to notify the upstream router. The leader also responds to ARP and NDP requests. In the BGP mode, each of the nodes establishes peering connection with the upstream router, announces themselves as a next hop of the service IP, and as a result, ECMP routing table can be created in the upstream router. Once the ingress traffic reaches one of the nodes, the packets are directed to existing *pods* by the internal load balancer. The problems with this implementation are as follows: In the case of the layer 2 mode, failover is slow (more than about 10 secs) [71]. The ingress traffic is distributed to all of the nodes. It is impossible to localize the routes to a limited number of the nodes.

	OSS	Container friendly	Redundancy	Forwarding	L3DSR
Conventional	No	No*	Static	iptables DNAT/IPVS	No
Nginx-ingress	Yes	Yes	No	nginx	No
kube-keepalived	Yes	Yes	VRRP	IPVS	No
Metallb	Yes	Yes	ECMP**	IPVS	No
This work	Yes	Yes	ECMP	IPVS***	IPIP

Table 6.1: Comparison of software load balancers for Kubernetes. * Conventional technology uses cloud load balancers if available, which is not necessarily container friendly. ** Metallb also supports layer 2 mode, which uses unsolicited ARP or NDP packets to update layer 2 address table in the upstream router. *** The author plans to add XDP feature in future work.

Table 6.1 compares key features for above mentioned load balancers. Regarding the redundancy, ECMP is better than VRRP because all the load balancer are active in the former case whereas only one of the load balancer is active in the latter. As far as the L3DSR feature is concerned, the load balancer with this feature is beneficial because of the better performance. The proposed load balancer is better than those in related works in these respects.

The proposed load balancer in this study differs in that it is deployed as part of a web application, giving the full control of the routing to the users rather than leaving them to the cluster administrators. This will help resolve issues when there are routing problems.

6.3 Cloud load balancers

As far as the cloud load balancers are concerned, two articles and one open source project have been identified.

Google's Maglev [16] is a software load balancer used in Google Cloud Platform(GCP). Maglev uses modern technologies including per flow ECMP and kernel bypass for user space packet processing.

Resulting performance provided by single hardware has been more than sufficient for 10 Gbps network.

Maglev serves as the GCP's load balancer that is used by the Kubernetes. Maglev is not a product that users can use outside of GCP nor is an open source software, while the users need open source software load balancer that can run even in on-premise data centers.

Microsoft's Ananta [17] is another software load balancer implementation using ECMP and Windows Filtering Platform based kernel-mode driver.

Ananta can be solely used in Microsoft's Azure cloud infrastructure[17]. The proposed load balancer by the author is different in that it aims to be used in every cloud provider and on-premise data centers.

Facebook's Katran [72] is an OSS software load balancer using Linux XDP technology.

Katran also uses ECMP for redundancy. Although Katran is expected to have high performance levels, no data has been shown yet. The proposed load balancer in this thesis aims to be portable using container technology while Katran has no such features.

	OSS	Container friendly	Redundancy	Forwarding	L3DSR
Maglev	No	No	ECMP	Flexible I/O layer	GRE
Ananta	No	No	ECMP	Windows Filtering Platform	IPIP
Katran	Yes	No	ECMP	XDP	IPIP
This work	Yes	Yes	ECMP	IPVS (XDP in future)	IPIP

Table 6.2: Cloud load balancer comparison.

Regarding the cloud load balancers, Maglev and Ananta try to differentiate their own cloud infrastructure by seeking the best performances. On the other hand, this study attempts to provide a load balancer common to any infrastructure by using standard OSS technologies.

Katran is an OSS software load balancer and hence can be used outside of their infrastructure. The proposed load balancer in this thesis differs in that it is portable due to containerization, and it is integrated with container infrastructure. Despite these differences, the technology components used in this work and the cloud load balancers are similar, which indicates that the proposed load balancer is state of the art.

6.4 Load balancer tools in the container context

There are several other projects where efforts have been made to utilize ipvs in the context of container environment. For example, GORB[73] and clusterf[74] are daemons that setup ipvs rules in the kernel inside the Docker container. They utilize running container information stored in key-value storages like Core OS etcd[34] and HashiCorp's Consul[75]. Although these were usable to implement a containerized load balancer in our proposal, the author did not use them, since Kubernetes ingress framework already provided the methods to retrieve running container information through standard API. These are merely alternative technology components used in this study.

6.5 Summary

In this chapter, the author presented the related work regarding the following subjects: (1) Portability of web applications. (2) Ingress routing in Kubernetes. (3) Cloud load balancers. (4) Load balancer tools in the container context.

There have been numerous works regarding the portability of web applications. This study is more focused on practical architecture and verification of its feasibility.

While the author proposes a portable load balancer for container clusters and verifies its feasibility using Kubernetes,

other groups also have proposed ingress routing using IPVS for Kubernetes. Compared with those related works, the proposed load balancer in this study differs in that it is deployed as part of a web application. Giving the full control of the routing to the users rather than leaving them to the cluster administrators will help resolve issues when there are problems.

Regarding the cloud load balancers, all of them try to differentiate their own cloud infrastructure by seeking the best performances. On the other hand, this study attempts to provide a load balancer common to any infrastructure by using standard OSS technologies. Despite the differences in purpose, the technology components used in this work and the related work are similar, which indicates that the proposed load balancer is state of the art.

Chapter 7

Conclusion

7.1 Conclusions

As the web services become an indispensable part of the daily life, portability of the application becomes very important. In order to improve the portability of web applications consisting of container clusters, container orchestrators need to be able to serve as a uniform platform by functioning as a common middleware.

However, they fail to do so, because none of the existing container orchestrators can fully automate the setup of routes for ingress traffic from the Internet.

To solve this problem, the author proposed an architecture using a portable software load balancer that can run on any infrastructure. The author proposed a cluster of software load balancers in containers that can be launched as a part of web applications for Kubernetes.

The proposed architecture is also capable of setting up the routes for the ingress traffic automatically in a redundant and scalable manner. For that purpose, Equal Cost Multi Path(ECMP) routes are populated through Border Gateway Protocol(BGP). Since both ECMP and BGP are the standard protocols, they are very likely to be supported by most of the upstream routers. By using the proposed architecture, container clusters no longer depend on the load balancers provided by infrastructures. And hence, container orchestrators become being able to better serve as a common middleware, which will improve the portability of the web applications consisting of container clusters.

To prove the feasibility of the proposed load balancer architecture, the author has implemented a containerized software load balancer using Linux kernel's IPVS for Kubernetes, and carried out experiments with the following criteria:

1) verify if the proposed load balancer works correctly both in the cloud and the on-premise data center. 2) verify if the proposed load balancer has a sufficient performance level for 1 Gbps and 10 Gbps networks. 3) verify if the proposed redundancy architecture using ECMP with BGP properly functions.

From the results of the experiments, it has been shown that the

throughput of the proposed load balancer linearly increases as the number of nginx *pod*s increases, and then it eventually saturates, indicating that the load balancer functions properly. It has been also shown that the proposed load balancers can run in an on-premise data center, Google Cloud Platform (GCP) and Amazon Web Service (AWS). Therefore the proposed load balancers can be said to be portable.

The throughputs of a load balancer are dependent on the settings for multi-core packet processing and the setting for the overlay network. To derive the best performance, the author used as many CPU cores as possible for packet processing, and the settings without any packet encapsulation for backend mode of the overlay network.

From the experiment in the 1 Gbps network environment, the author obtained the highest throughput for the IPVS-TUN (L3DSR) in a container, which is limited by the bandwidth of the benchmark client. Since the benchmark client is placed at the same location where the upstream router exists, the load balancer can be said to have sufficient performance to fill up 1 Gbps network bandwidth.

The author also extended the throughput measurement into the 10 Gbps network environment, in order to verify that proposed software load balancer is capable of providing needed throughput for 10

Gbps environment. The throughputs of IPVS and IPVS-TUN are smaller than that of iptables DNAT in 10Gbps network, both due to the overhead of the container network and inefficiency in the program itself. Considering the fact that the throughput of the whole system never exceeds that of the upstream router at the entrance, the load balancers only need to be able to handle at most 2.9M [req/sec] in 10Gbps network. This can be easily achieved using four of the IPVS-TUN (L3DSR) load balancer container since a single IPVS-TUN in a container can handle 731K [req/sec]. Therefore the author also concludes that although there is a room for improvements the proposed load balancer has sufficient performance for 10 Gbps network environment.

The author has also implemented an automatic setup of the ECMP route for ingress traffic. There, multiple load balancer containers are deployed, and each of them advertises itself as an active next hop of the IP for web application through Border Gateway Protocol (BGP). The ECMP route makes the load balancers redundant and scalable since all the load balancer containers act as active. The BGP helps automatic setup of the ECMP route. The BGP and ECMP are both standard protocols supported by most of the commercial router products. The author verified through experiment that an ECMP route has been automatically created upon launch of a new load balancer container on the upstream router. The update of the ECMP routing table was correct and quick enough, i.e., within 10 seconds, throughout 20 hours experiment. The maximum performance levels of the cluster of load balancers have scaled linearly up to four times as the number of the load balancer containers has been increased to four of them. The maximum aggregated throughput obtained through the experiment is 780k [req/sec], which is limited by the CPU performance of the benchmark client, and therefore can be improved using better hardware in the future experiment. Therefore the author has proved that proposed load balancer has the capability of the automatic setup of ingress traffic in a redundant and scalable manner.

Sooner or later, the day when the network in a data center becomes all 100 Gbps will come.

Therefore, in the future, it becomes crucial to improve the throughput of portable load balancers by using better container network and implementing more efficient software load balancer itself. The author leaves these for future work, however, a preliminary result of the latter has also been presented. The author has implemented a software load balancer using XDP technology and carried out throughput measurement. The current implementation does not support multicore packet processing, and hence throughput is limited by the capability of single core processing performance. Nevertheless, the obtained throughput about 390K [req/sec] for the XDP load balancer indicates that this technology is very promising. The author estimates that about five of the software load balancer using this technology with 16 core packet processing can provide enough throughput, 29M [req/sec] in 100 Gbps environments in the future.

The proposed load balancer has been verified to be portable while providing sufficient throughput in 10 Gbps environment.

And the proposed redundancy architecture using ECMP with BGP has also been verified to function properly. As a consequence, the proposed architecture with this load balancer will help improve the portability of web applications.

The outcome of this study will benefit users who want to deploy their web services on any cloud provider where no scalable load balancer is provided, to achieve high scalability. Moreover, the result of this study will potentially benefit users who want to use a group of different cloud providers and on-premise data centers across the globe seamlessly. In other words, users will become being able to deploy a complex web service on aggregated computing resources on the earth, as if they were starting a single process on a single computer.

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Appendix A

ingress controller

```
package main

import (
        "log"
        "net/http"
        "os"
        "syscall"
        "os/exec"
        "strings"
        "text/template"
        "github.com/spf13/pflag"
        api "k8s.io/client-go/pkg/api/v1"
        nginxconfig "k8s.io/ingress/controllers/nginx/pkg/config"
        "k8s.io/ingress/core/pkg/ingress"
        "k8s.io/ingress/core/pkg/ingress/controller"
        "k8s.io/ingress/core/pkg/ingress/defaults"
)

var cmd = exec.Command("keepalived", "-nCDlf", "/etc/keepalived/ipvs.conf")

func main() {
        ipvs := newIPVSController()
        ic := controller.NewIngressController(ipvs)
        cmd.Stdout = os.Stdout
        cmd.Stderr = os.Stderr
        cmd.Start()
        defer func() {
                log.Printf("Shutting down ingress controller...")
                ic.Stop()
        }()
        ic.Start()
}

func newIPVSController() ingress.Controller {
        return &IPVSController{}
}

type IPVSController struct{}

func (ipvs IPVSController) SetConfig(cfgMap *api.ConfigMap) {
        log.Printf("Config map %+v", cfgMap)
}

func (ipvs IPVSController) Reload(data []byte) ([]byte, bool, error) {
        cmd.Process.Signal(syscall.SIGHUP)
        out, err := exec.Command("echo", string(data)).CombinedOutput()
```

```
        if err != nil {
                return out, false, err
        }
        log.Printf("Issue kill to keepalived. Reloaded new config %s", out)
        return out, true, err
}

func (ipvs IPVSController) OnUpdate(updatePayload ingress.Configuration) ([]byte, error)
    ↪ {
        log.Printf("Received OnUpdate notification")
        for _, b := range updatePayload.Backends {
                type ep struct{
                        Address,Port string
                }
                eps := []ep{}
                for _, e := range b.Endpoints {
                        eps = append(eps, ep{Address: e.Address, Port: e.Port})
                }

                for _, a := range eps {
                log.Printf("Endpoint %v:%v added to %v:%v.", a.Address, a.Port, b.Name, b
                    ↪ .Port)
                }

                if b.Name == "upstream-default-backend" {
                        continue
                }
                cnf := []string{"/etc/keepalived/ipvs.d/" , b.Name , ".conf"}
                w, err := os.Create(strings.Join(cnf, ""))
                if err != nil {
                        return []byte("Ooops"), err
                }
                tpl := template.Must(template.ParseFiles("ipvs.conf.tmpl"))
                tpl.Execute(w, eps)
                w.Close()
        }

        return []byte("hello"), nil
}

func (ipvs IPVSController) BackendDefaults() defaults.Backend {
        // Just adopt nginx's default backend config
        return nginxconfig.NewDefault().Backend
}

func (ipvs IPVSController) Name() string {
        return "IPVS Controller"
}

func (ipvs IPVSController) Check(_ *http.Request) error {
        return nil
}

func (ipvs IPVSController) Info() *ingress.BackendInfo {
```

```
        return &ingress.BackendInfo{
                Name:       "dummy",
                Release:    "0.0.0",
                Build:      "git-00000000",
                Repository: "git://foo.bar.com",
        }
}

func (ipvs IPVSController) OverrideFlags(*pflag.FlagSet) {
}

func (ipvs IPVSController) SetListers(lister ingress.StoreLister) {
}

func (ipvs IPVSController) DefaultIngressClass() string {
        return "ipvs"
}
```

Appendix B

ECMP settings

B.1 Exabgp configuration on the load balancer container.

B.2 Gobgpd and zebra configurations on the router.

gobgp.conf:

```
global:
  config:
    as: 65021
    router-id: 10.0.0.110
    local-address-list:
    - 0.0.0.0

  use-multiple-paths:
    config:
      enabled: true

neighbors:
    - config:
        neighbor-address: 10.0.0.109
        peer-as: 65021
      add-paths:
        config:
          receive: true

zebra:
  config:
    enabled: true
    url: unix:/run/quagga/zserv.api
    version: 3
    redistribute-route-type-list:
      - static
```

The "use-multiple-paths" should be enabled for the gobgpd to redistribute BGP multipath routes to Zebra.

zebra.conf:

```
hostname Router
log file /var/log/zebra.log
```

B.3 Gobgpd configuration on the route reflector.

gobgp.conf:

```
global:
  config:
    as: 65021
    router-id: 10.0.0.109
    local-address-list:
    - 0.0.0.0 # ipv4 only
  use-multiple-paths:
    config:
      enabled: true

peer-groups:
  - config:
      peer-group-name: k8s
      peer-as: 65021
    afi-safis:
      - config:
          afi-safi-name: ipv4-unicast

dynamic-neighbors:
  - config:
      prefix: 172.16.0.0/16
      peer-group: k8s

neighbors:
  - config:
      neighbor-address: 10.0.0.110
      peer-as: 65021
    route-reflector:
      config:
        route-reflector-client: true
        route-reflector-cluster-id: 10.0.0.109
    add-paths:
      config:
        send-max: 255
        receive: true
```

The "dynamic-neighbors" section and the "peer-groups" section set up dynamic neighbor settings to avoid listing of every possible IP. The "add-paths" setting in the "neighbors" section enables multi path advertisement for a single network prefix.

B.4 Exabgp configuration on the load balancer container.

exabgp.conf:

```
neighbor 10.0.0.109 {
 description "peer1";
 router-id 172.16.20.2;
 local-address 172.16.20.2;
 local-as 65021;
 peer-as 65021;
 hold-time 1800;
   static {
     route 10.1.1.0/24 next-hop 10.0.0.106;
   }
}
```

The IP address of the load balancer pod(i.e. container), "172.16.20.2", is used for "router-id" and "local-address". This address is dynamically assigned when the pod is started. The IP address of the node, "10.0.0.106", is used for "next-hop". The node address is found out when the pod starts.

Appendix C

Analysis of the performance limit

The maximum throghput in this series of experiment is roughly, 190k[req/sec] for both ipvs an the iptables DNAT. At first, it was not clear what caused this limit. The author analyzed the kind of packets that flows during the experiment using tcpdump[76] as follows; 1) A wrk worker opens multiple connections and sends out http request to the web servers. The number of connections is determined by the command-line option, eg. 800/40 = 20 connection in the case of command-line in Table 4.1. The worker sends out 100 requests to the web server within each connection, and closes it either if all of the responses are recieved or time out occurs. 2) As in seen in Listing C.1, tcp options were mss(4 byte), sack(2 byte), ts(10 byte), nop(1 byte) and wscale(3 byte), for SYN packets. For other packets, tcp options were, nop(1 byte), nop(1 byte) and ts(10 byte). 3) The author classified the types of packes and counted the number of each type in a single connection, which is 100 http requests. Table C.1,C.2,C.3 summarize the data size of 100 request, including TCP headr, IP header, Ether header and overheads. From this analysis, it was found that per each HTTP request and response, request data with the size of 227.68[byte] and response data with the data(http content)+437.68[byte] were being sent.

Since the node for load balancer recives and transmits both request and response packets using single network interface, each 1Gbps half duplex of full duplex must accomodate request and response data size. Therefore the theoretical maximum throughput can be expressed as;
throughput[req/sec] = bandwidth[byte/sec]/(request + response)
= 1e9/8/(data+665.36)

Figure C.1 shows plot of theoretical maximum throughput 1Gbps ethernet together with actual benchmark results. Since experimnetal results agrees well with theory, the author concludes that when “RPS = on”, ipvs performance limit is due to the 1Gbps bandwidth.

```
1  curl -s  http://172.16.72.2:8888/1000
2  tcpdmup(response):
3
4  03:09:27.968942 IP 172.16.72.2.8888 > 192.168.0.112.60142:
5  Flags [S.], seq 2317920646, ack 648140715, win 28960, options [mss 1460,sackOK,TS val
       2274012282 ecr 2324675546,nop,wscale 8], length 0
6  03:09:27.969685 IP 172.16.72.2.8888 > 192.168.0.112.60142:
7  Flags [.], ack 85, win 114, options [nop,nop,TS val 2274012282 ecr 2324675546], length
       0
8  03:09:27.969945 IP 172.16.72.2.8888 > 192.168.0.112.60142:
9  Flags [P.], seq 1:255, ack 85, win 114, options [nop,nop,TS val 2274012282 ecr
       2324675546], length 254
10 03:09:27.969948 IP 172.16.72.2.8888 > 192.168.0.112.60142:
11 Flags [P.], seq 255:1255, ack 85, win 114, options [nop,nop,TS val 2274012282 ecr
       2324675546], length 1000
12 03:09:27.970846 IP 172.16.72.2.8888 > 192.168.0.112.60142:
13 Flags [F.], seq 1255, ack 86, win 114, options [nop,nop,TS val 2274012282 ecr
       2324675547], length 0
```

Listing C.1: An example of the tcpdump output

Type of Packet	Payload [byte]	Header [byte]	Count	Total [byte]
SYN	0	98	1	98
ACK	0	90	102	9,180
Push(GET)	44	90	100	13,400
FIN+ACK	0	90	1	90
Total				22,768

Table C.1: Request data size for 100 HTTP requests in wrk measurement.

Type of Packet	Payload [byte]	Header [byte]	Count	Total [byte]
SYN+ACK	0	98	1	98
ACK	0	90	2	180
Push(GET)	254	90	100	34,400
Push(DATA)	data	90	100	100x(data+90)
FIN+ACK	0	90	1	90
Total				100x(data+90)+34,768

Table C.2: Response data size for 100 HTTP requests in wrk measurement.

Type of field	SYN	ACK, SYN+ACK, FIN+ACK, PUSH
preamble	8	8
ether header	14	14
ip header	20	20
tcp header	20 + 20(tcp options)	20 + 12(tcp options)
fcs	4	4
inter frame gap	12	12
Total [byte]	98	90

Table C.3: Header sizes of TCP/IP packet in Ethernet frame.

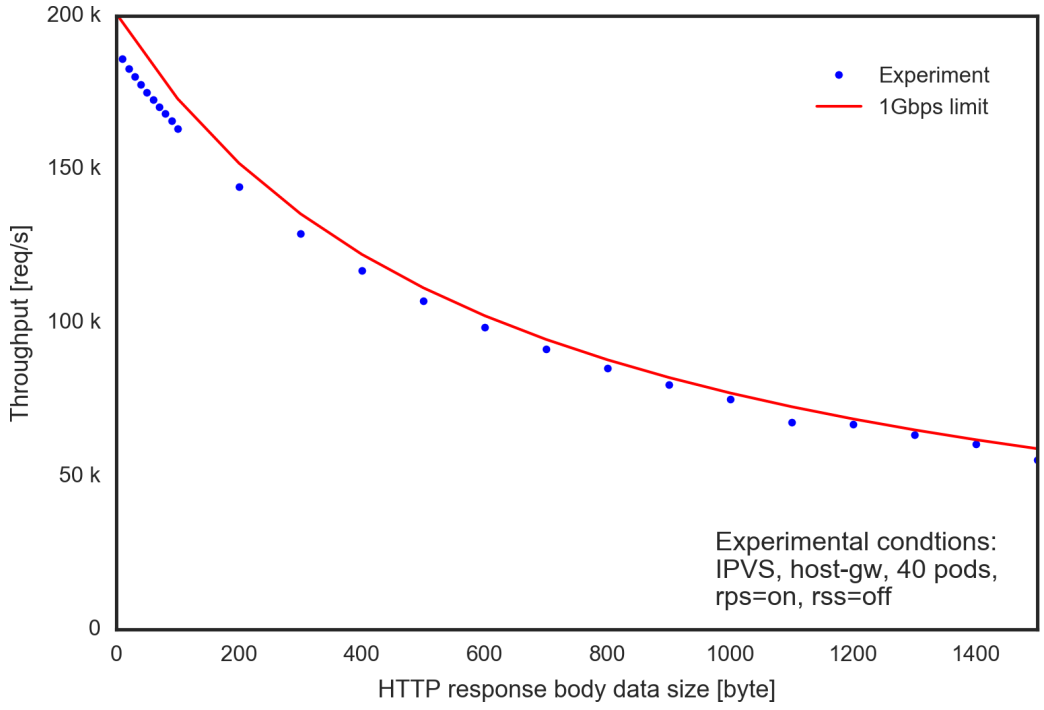

Figure C.1: Perfomance limitation due to 1Gbps bandwidth.

Appendix D

VRRP

The authors have considered another redundant architecture using the VRRP protocol. However, it turned out to be less preferable than the proposed ECMP redundancy with following reasons; (a)Redundancy is in an active-backup manner. (b)The VRRP protocols relied on multicast, which is often not supported in the overlay network environments. Here, the author explain our considerations.

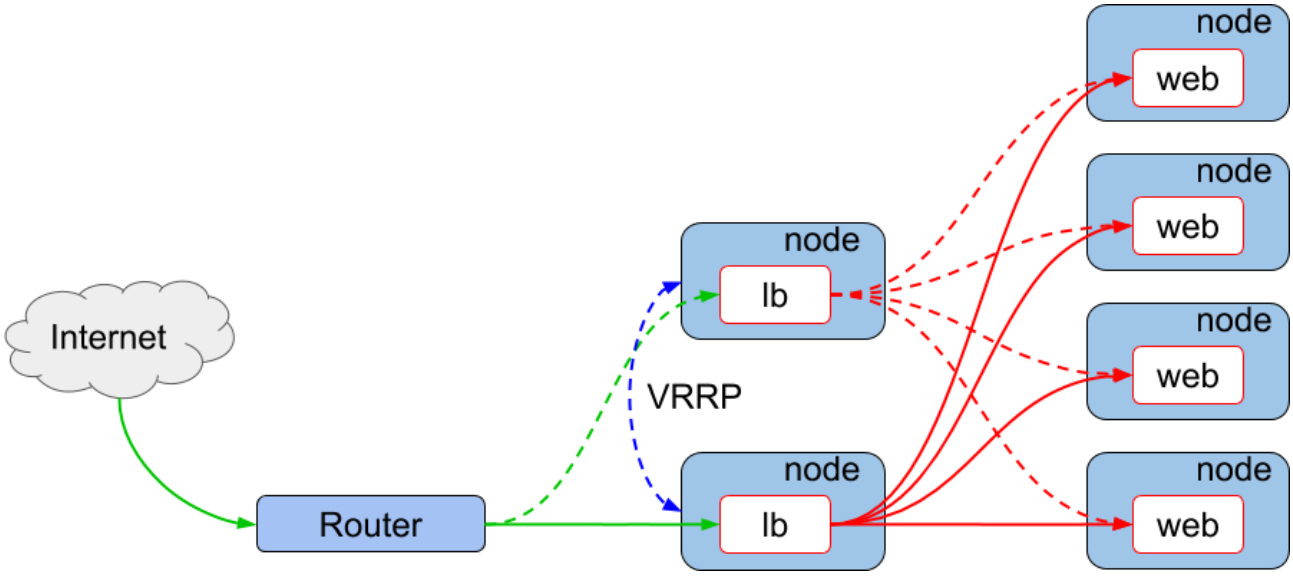

Figure D.1: An alternative redundant load balancer architecture using VRRP.
The traffic from the internet is forwarded by the upstream router to a active lb node(the solid green line) and then distributed by the lb pods to web pods using Linux kernel's ipvs(the solid red line). The active lb pod is selected using VRRP protocol(the blue dotted line). For the green lines global IP address is used. The red lines use IP addresses of overlay network. The blue line uses the IP address of node network.

Fig. D.1 shows the redundancy setup using the VRRP protocol. In the case of VRRP, the load balancer container needs to run in the node net namespace for the following two reasons; 1) When fail over occurs, the new master sends gratuitous Address Resolution Packets(ARP) packets to update the ARP cache of the upstream router and Forwarding Data Base(FDB) of layer 2 swicthes during the transition. Such gratuitous ARP packets should consist of the virtual IP address shared by the load balancers and the MAC address of the node where the new master load balancer is running. Programs that send out gratuitous ARP with node MAC address should be in the node net namespace. 2) Furthermore, the active load balancer sends out periodic advertisement using UDP multicast packet to inform existence of itself. The load balancer in backup state stays calm unless the VRRP advertisement stops for a specified duration of time. The UDP multicast is often unsupported in overlay network used by container cluster environment, and hence the load balancer needs to be able to use the node net namespace. Running containers in the node net namespace loses the whole point of containerization, i.e., they share the node network without separation. This requires the users' additional efforts to avoid conflict in VRRP configuration for multiple services.

VRRP programs also support unicast advertisement by specifying IP addresses of peer load balancers

before it starts. However, container cluster management system randomly assign IP addresses of containers when it launches them, and it is impossible to know peer IPs in advance. Therefore the unicast mode is not feasible in container cluster environment.

The other drawback compared with the ECMP case is that the redundancy of VRRP is provided in Active-Backup manner. This means that a single software load balancer limits the overall performance of the entire container cluster. Therefore, the author believes that the ECMP redundancy is better than VRRP.