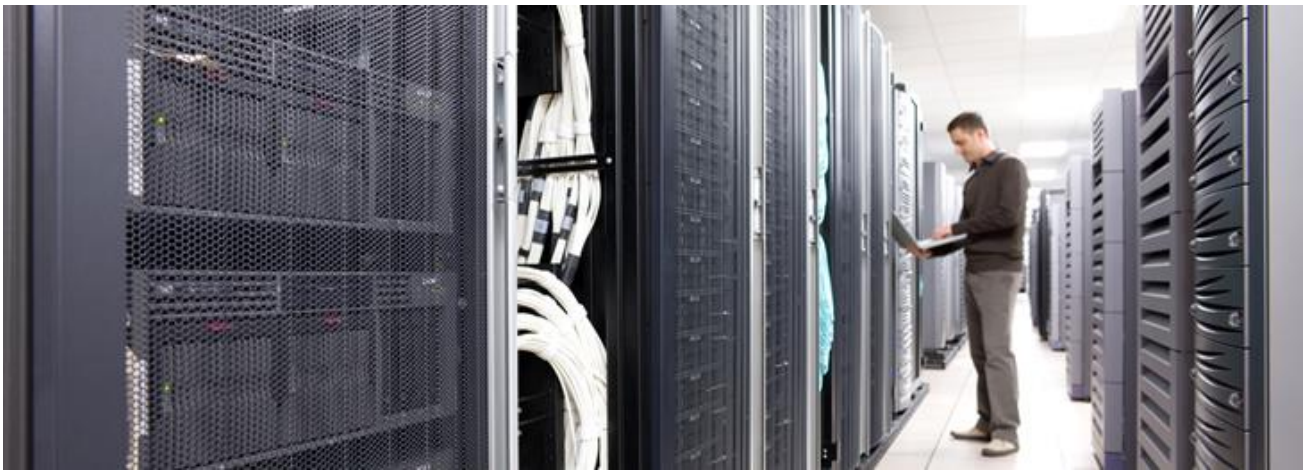
ACI Plugin for Red Hat OpenShift Container Architecture and Design Guide



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1. Introduction

Container technology is becoming increasingly popular in all kinds of IT organizations. Containers facilitate packaging applications and making them portable. Container scheduler frameworks, such as Kubernetes, provide the means to deliver software from development into production at scale, with agility and at a fraction of the cost of previous models based on Virtual Machines and sophisticated cloud and application management.

The Red Hat OpenShift Container Platform is an enterprise-grade platform as a service based on Kubernetes that enables Enterprise customers to adopt container technology to develop and run applications. Most organizations that adopt Red Hat OpenShift require enterprise-grade network and security also face challenges when connecting newly developed applications with other environments such as Enterprise Databases, Data warehouses, Big Data clusters, mainframes or applications running in legacy virtualization technologies in general.

The Cisco ACI CNI plugin for the Red Hat OpenShift Container Platform provides a single, programmable network infrastructure that eliminates bottlenecks between OpenShift workloads and the rest of the infrastructure while providing enterprise-grade security and offers flexible micro segmentation possibilities.

In this document, we describe in detail the architecture, operation and design possibilities of the Cisco ACI CNI plugin for Red Hat OpenShift.

This document assumes the reader possesses basic knowledge of Cisco ACI, Kubernetes and Red Hat OpenShift.

2. Cisco ACI CNI Plugin

By default, Docker containers connect to a Linux bridge on the node where the docker daemon is running. To allow connectivity between those containers and any endpoint external to the node, port-mapping and/or NAT are required, which complicates Docker networking at scale.

The Kubernetes networking model was conceived to simplify Docker container networking. First, Kubernetes introduces the concept of a Pod that allows multiple containers to share a single IP namespace and thus communicate over localhost.

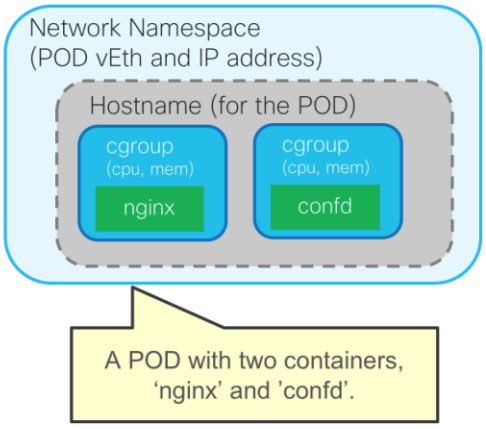

Figure 1: Example of Kubernetes Pod

Second, Kubernetes assumes two key premises for Pod networking:

- Every Pod must be able to communicate with each other Pod in the cluster without NAT.
- Kubelet on every node must be able to communicate with every Pod in the cluster without NAT.

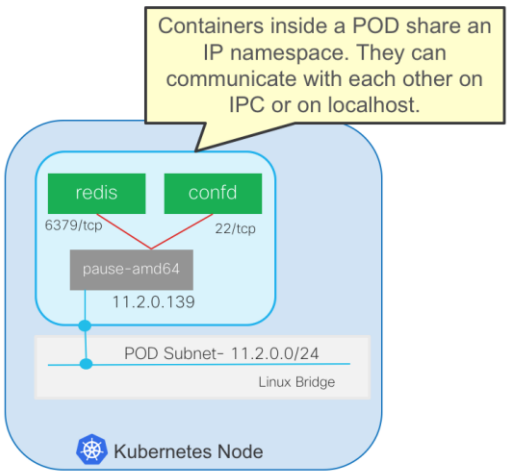

Figure 2: Kubernetes Pod networking example

However, Kubernetes has a modular approach to how networking is implemented. Specifically, networking is implemented via the Container Network Interface (CNI) model of plugins.

Each CNI plugin must be implemented as an executable that is invoked by the container management system. A CNI plugin is responsible for inserting a network interface into the container network namespaces (e.g. one end of a veth pair) and making any necessary changes on the host (for example, attaching the other end of the veth to a bridge). It should then assign an IP to the interface and also setup the routes consistent with the IP address Management section by invoking the appropriate IPAM plugin.

Cisco's Application Policy Infrastructure Controller (APIC) can integrate with Kubernetes clusters using a Cisco-developed CNI plugin. With this plugin, one or more Kubernetes clusters can be integrated with a Cisco ACI fabric. The APIC can provide all networking needs for the workloads in the cluster. Kubernetes workloads become fabric endpoints, just like Virtual Machines or Bare Metal endpoints. The Cisco ACI CNI plugin is 100% Open Source and relies on the Opflex Protocol to program Open vSwitch instances running on the Kubernetes nodes.

A CNI plugin is implemented as a binary file accompanied by the necessary control elements and configuration objects. The CNI binaries are typically placed under /opt/cni/bin/ although a different location can be used, if specified by the kubelet configuration parameter cni-bin-dir. We can see in the example below the content of the opflex-agent-cni plugin directory that it uses when running the Cisco ACI CNI plugin:

```
[root@ocp-bm-master ~]# ls -la /opt/cni/bin/
total 9064
drwxr-xr-x. 2 root root      46 Nov  5 11:21 .
drwxr-xr-x. 3 root root      17 Oct 31 17:01 ..
-rwxr-xr-x. 1 root root 3026388 Nov  5 11:21 loopback
-rwxr-xr-x. 1 root root 6253472 Nov  5 11:21 opflex-agent-cni
[root@ocp-bm-master ~]#
```

Figure 3

In the Container Network Interface model, a network is a group of endpoints that are uniquely addressable and can communicate with each other. An endpoint can be a container, a host or any network device. The configuration of a network is defined in a JSON formatted file. In the example below, we can see an example a network configuration when using the Cisco ACI CNI plugin:

```
[root@ocp-bm-master ~]# cat /etc/cni/net.d/10-opflex-cni.conf
{
   "cniVersion": "0.3.1",
   "supportedVersions": [ "0.3.0", "0.3.1" ],
   "name": "k8s-pod-network",
   "type": "opflex-agent-cni",
   "ipam": {"type": "opflex-agent-cni-ipam"}
}
[root@ocp-bm-master ~]#
```

Figure 4

The configuration file along with the opflex-agent-cni binary must exist in every node in a cluster. This binary allows the APIC to provide networking, security and load balancing services to the workloads in the cluster.

The Cisco ACI CNI plugin implements the following features:

- IP Address Management for Pods and Services
- Distributed Routing and Switching with integrated VXLAN overlays implemented fabric wide and on Open vSwitch
- Distributed Load Balancing for ClusterIP services
- Hardware-accelerated Load Balancing for External LoadBalancer services
- Distributed Firewall for implementing Network Policies
- EPG-level segmentation for Kubernetes objects using annotations
- Consolidated visibility of Kubernetes networking via APIC VMM Integration

3. Red Hat OpenShift Container Platform (OCP) Primer

OpenShift Container Platform (formerly known as OpenShift Enterprise) or OCP is Red Hat's offering for on-premises private platform as a service (PaaS). OpenShift is based on the Origin open source project. It is a distribution of Kubernetes optimized for continuous application development and multi-tenant deployment. Origin adds a series of security features plus developer and operations-centric tools on top of Kubernetes to enable rapid application development, easy deployment and scaling.

OCP provides many components required to develop and run applications in Enterprise or Service Provider environments, such as a container registry, administration web console interface, monitoring and performance management and a catalog of software and databases ready to use for developers.

3.1. OpenShift Container Platform Networking

OCP networking relies on the Kubernetes CNI model. OCP supports various plugins by default as well as several commercial SDN implementations including Cisco ACI. The CNI plugin to be used must be defined at installation time, typically in an Ansible playbook that kicks off the installation process[1].

The native plugins rely on Open vSwitch and offer alternatives to providing segmentation using VXLAN or the Kubernetes Network Policy objects listed below:

- ovs-subnet
- ovs-multitenant
- ovs-networkpolicy

OpenShift offers a special type of ingress controller to expose applications via a reverse proxy based on HA Proxy called the OpenShift router. The OpenShift router allows developers and OCP administrators to automatically expose applications on a cluster-specific URL. The URL for a given application, called an OpenShift route, is

[1] https://github.com/openshift/openshift-ansible/pull/8221 pending

automatically programmed on the OpenShift router to proxy the traffic to the right application backend. This model also allows exposing applications using plain HTTP or TLS by providing certificates to the OpenShift cluster. Administrators can use common Kubernetes objects to expose services, including NodePort or LoadBalancer objects. In fact, the OpenShift router is itself exposed as a Kubernetes LoadBalancer service.

OpenShift routers are used for exposing services provided by the cluster, that is, to allow external endpoints to reach the cluster. There are times when an application running on the cluster needs to initiate a connection to an external endpoint. In those cases, the native OpenShift CNI plugins rely on "external routers" and/or on a tunnel interface on every OpenShift node that provides a NAT connection with the node's host address.

4. Running Cisco ACI and OpenShift

When running OpenShift clusters connected to ACI fabrics, customers can still choose to use any of the native OpenShift SDN options, using ACI as a simple transport underlay layer and connecting to other workloads by leveraging egress routers.

Customers implementing OpenShift clusters using the native SDN technologies are often confronted with various challenges, including the following:

- Applications running in OpenShift Pods that need high-bandwidth, low-latency traffic to data external to the cluster suffer the bottleneck imposed by the egress router implementation.
- It is difficult to control which applications in the cluster have access to external resources.
- Exposing L4 services requires using external load balancers with added complexity and limited performance.
- Segmentation and security internal to the cluster can only be done by cluster administrators using NetworkPolicy.
- Network and Security teams have limited to no visibility into OpenShift workloads, making day-2 troubleshooting particularly cumbersome.

The Cisco ACI CNI plugin for Red Hat OpenShift Container Platform provides a cost-effective solution to these challenges when implementing production-level OpenShift clusters. The ACI CNI plugin enhances OpenShift in these ways:

- Unified networking: by extending the integrated overlay of the ACI fabric to OpenShift workloads, Pod and Service endpoints become first class citizens at the same level as Bare Metal or Virtual Machines.
- High performance, low-latency secure connectivity without egress routers: a consequence of the previous point, Pods can easily connect with other fabric or non-fabric endpoints leveraging the combined hardware and software distributed routing and switching provided by ACI and the ACI CNI plugin.
- Granular security: security can be implemented by using native NetworkPolicy or by using ACI EPGs and contracts, or both models complementing each other.
- Simplified Operations and Enhanced visibility: whether policies and networking are defined by the devops or fabric or security admins the APIC becomes the single source of truth for operations and security governance.
- Hardware-assisted load balancing of ingress connections to LoadBalancer-type services using ACI's Policy Based Redirect technology

The ACI CNI plugin provides many benefits to OpenShift operators while allowing complete transparency for users and developers. The following table compares various features between the native OpenShift CNI plugin offerings and the ACI CNI plugin.

	ovs-subnet	ovs-multitenant	ovs-networkpolicy	ACI CNI Plugin
IPAM	Yes	Yes	Yes	Yes
Networking	Cluster Only	Cluster Only	Cluster Only	Containers, VM, Bare Metal
NetworkPolicy	No	No	Cluster Only	Yes
ClusterIP	Yes	Yes	Yes	Yes
LoadBalancer	No	No	No	Yes
Egress Routers	Required	Required	Required	Not Required
Ingress Routers	HAProxy	HAProxy	HAProxy	HAProxy
External Segmentation	No	No	No	Yes, EPG with annotations
Added Security	No	No	No	Yes, ACI Contracts, NGFW Insertion
Common Network Operations	No	No	No	Yes, APIC visibility

Table 1

5. Cisco ACI CNI Plugin for OpenShift Architecture

The Cisco ACI CNI Plugin for OpenShift Container Platform provides integration between the APIC controller and one or more OpenShift clusters connected to a Cisco ACI fabric. This integration is implemented across two main functional areas:

1. The Cisco ACI CNI plugin extends the ACI fabric capabilities to OpenShift clusters in order to provide IP Address Management, networking, load balancing and security functions for OpenShift workloads. The Cisco ACI CNI plugin connects all OpenShift Pods to the integrated VXLAN overlay provided by Cisco ACI.
2. The Cisco ACI CNI Plugin models the entire OpenShift cluster as a VMM Domain on the Cisco APIC. This provides APIC with access to the inventory of resources of the OpenShift cluster, including the number of OpenShift nodes, OpenShift namespaces, services, deployments, Pods, their IP and MAC addresses, interfaces they are using, etc. APIC uses this information to automatically correlate physical and virtual resources in order to simplify operations.

The ACI CNI plugin is designed to be transparent for OpenShift developers and administrators and to integrate seamlessly from an operational standpoint. One of the main advantages of using the Cisco ACI CNI plugin for Red Hat OpenShift Container Platform is to allow applications running on OpenShift to communicate with applications running in other form factors such as bare metal, Virtual Machines or other container clusters, without constraints or performance bottlenecks. Simply map multiple domain types to the EPG of your choice and you have a mixed-workload environment in a matter of seconds! ACI takes care of bridging and routing VxLAN to VLAN, VxLAN to VxLAN and VLAN to VLAN automatically.

5.1. ACI CNI Plugin Components

The Cisco ACI CNI Plugin for Red Hat OpenShift Container Platform requires certain configuration steps to be performed on the Cisco ACI fabric and running several components as Pods on the OpenShift Cluster. Note that the deployment of those Pods as well as the required ACI configuration is automated to a large extent by tools provided by Cisco on cisco.com. Some of these components interact with functions implemented by processes running on the Cisco APIC or on the ACI leaf switches.

The Cisco ACI CNI plugin components that run on the OpenShift cluster are the following:

1. **ACI Containers Controller** (ACC, `aci-containers-controller`).

```
[root@oc-bm-master ~]# oc get deployments --namespace=aci-containers-system
NAME                          DESIRED   CURRENT   UP-TO-DATE   AVAILABLE   AGE
aci-containers-controller     1         1         1            1           1d
```

Figure 5

This is a Kubernetes deployment that runs the 'noiro/aci-containers-controller' docker image deployed to the 'aci-containers-system' project/namespace. This controller component communicates with both the cluster master and with the Cisco APIC. The ACC handles IP address management, load balancing for services, keeps track of endpoint state, and pushes configurations to APIC when required. The deployment runs only one instance of this Pod, and availability is implemented relying on the OpenShift/Kubernetes deployment controllers. This is a stateless Pod that can run on any node on the cluster.

2. **ACI Containers Host** (ACI, `aci-containers-host`).

```
[root@oc-bm-master ~]# oc get daemonsets --namespace=aci-containers-system
NAME                          DESIRED   CURRENT   READY   UP-TO-DATE   AVAILABLE   NODE SELECTOR   AGE
aci-containers-host           3         3         3       3            3           <none>          1d
aci-containers-openvswitch    3         3         3       3            3           <none>          1d
```

Figure 6

This is a daemonset running a Pod using the 'noiro/aci-containers-host' docker image. The daemonset configuration is such that this Pod runs once on every node of the OpenShift cluster, including the Master nodes. This Pod runs three containers:

   a. aci-containers-host: it is responsible for keeping endpoint metadata and configuring interfaces and IP addresses on Pods launched on the node.
   b. opflex-agent: it builds an Opflex channel with the ACI leaf (or leaves when using a vPC) to which the node is connected. This agent queries the ACI opflex proxy on the connected leaf to learn the policies required for a given Pod or service. It translates the learned policies into OpenFlow rules to be programmed on Open vSwitch.
   c. mcast-daemon: this daemon handles broadcast, unknown unicast and multicast packets on the node.

Below we can see the output of the daemonsets running on the aci-containers-systems namespace on a three node cluster.

3. **ACI Containers Open vSwitch** (ACI, `aci-containers-openvswitch`).

```
[root@oc-bm-master ~]# oc get daemonsets --namespace=aci-containers-system
NAME                        DESIRED   CURRENT   READY     UP-TO-DATE   AVAILABLE   NODE SELECTOR   AGE
aci-containers-host         3         3         3         3            3           <none>          1d
aci-containers-openvswitch  3         3         3         3            3           <none>          1d
```

Figure 7

This is another daemonset configured to run on every node in the cluster instance of a Pod using the 'noiro/aci-containers-openvswitch' docker image. The node's Open vSwitch uses this Pod as the control-plane only interface to program the required security policies, such as Kubernetes Network Policies or ACI Contracts.

The ACI Pods connect to the host local network. All other Pods in the cluster connect to opflex-configured networks. The ACI CNI plugin adds a configuration file under /etc/cni/net.d/ as follows (note, version numbering may change):

```
[root@ocp-bm-master ~]# cat /etc/cni/net.d/10-opflex-cni.conf
{
"cniVersion": "0.3.1",
"supportedVersions": [ "0.3.0", "0.3.1" ],
"name": "k8s-pod-network",
"type": "opflex-agent-cni",
"ipam": {"type": "opflex-agent-cni-ipam"}
}
[root@k8s-nested-master ~]#
```

Figure 8

In addition to the components running on the OpenShift cluster, there are some functions that are implemented on APIC and on the ACI fabric.

1. **ACI VMM Manager**. This process runs on the APIC cluster and communicates with the ACI Containers Controller to receive required configuration, such as Network Policies configured via Kubernetes as well as to learn about endpoints created or deleted on the OpenShift Cluster. The VMM object model for OpenShift represents many objects, such as namespaces, deployments, services and Pods. The VMM manager inventory is key to correlating information between the OpenShift cluster, the Open vSwitch and the Physical Fabric.
2. **ACI Leaf Opflex Proxy**. This process runs on the ACI leaf switches to scale out policy propagation to the connected nodes. When new Pods are launched by whatever means (a new deployment, or a scale out of an existing one), the ACI CNI Plugin components provides its interface and IP address configuration. In addition, they must know to which EPG the Pod must be connected and which security policies must be configured. This information exists on the APIC cluster. However, to avoid the opflex agent of every node querying the APIC directly, a two-tier scale out model is used. The opflex agent running on the node on the aci-containers-host Pod queries the ACI leaf to which it is connected. If the leaf has not received policy for the endpoint, it queries the APIC, transfers the result to the opflex agent of the node, caches the response, and implements any necessary configurations on the leaf, such as SVI and VRF, contracts if required, etc. The next time a Pod connects that requires the same policies, the answer to the opflex agent comes directly from the leaf.

When the OpenShift nodes receive configuration from the leaf via opflex, the opflex agent performs all required programming on the Open vSwitch of the node to implement the required network and security policies. This includes routing configuration, so the first hop router for every OpenShift Pod is always the local Open vSwitch of the node to which it is connected. The opflex agent implements other features in software on Open vSwitch . In particular, opflex programs Open vSwitch to perform distributed load balancing in order to implement ClusterIP services, as well as to run a stateful distributed firewall to implement Kubernetes Network Policies and stateless distributed firewall for ACI Contracts. In section 5.4 we explain how these features are implemented.

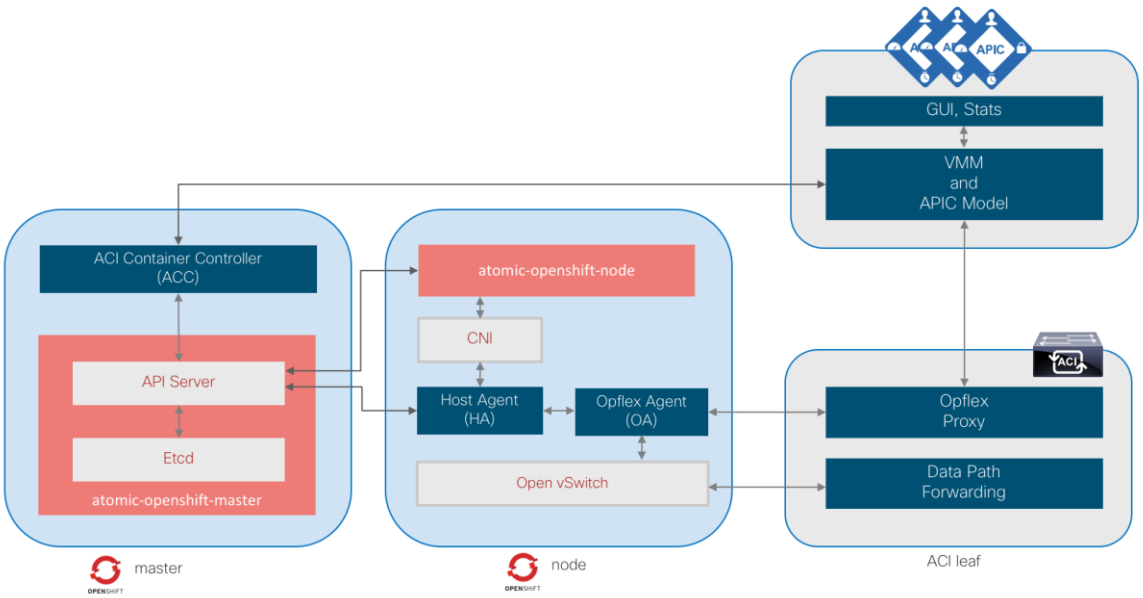

Figure 9: General ACI CNI Plugin architecture

5.2. Default ACI Application Profile Configuration and Tenancy Model

Cisco ACI is a multitenant system. The tenancy model in ACI implements isolation at the administrative and networking levels. Some resources in ACI are considered to be fabric-wide, while others may be tenant specific or shared between multiple tenants.

The Cisco ACI CNI Plugin for Red Hat OpenShift creates a VMM Domain to keep the OpenShift cluster inventory in APIC. This is a fabric admin resource. However, the OpenShift cluster as a collection of endpoints that must deployed to an ACI tenant. The OpenShift cluster can consume ACI configured resources such as L3Out interfaces which may be in the same tenant selected for the OpenShift cluster, or on the common tenant.

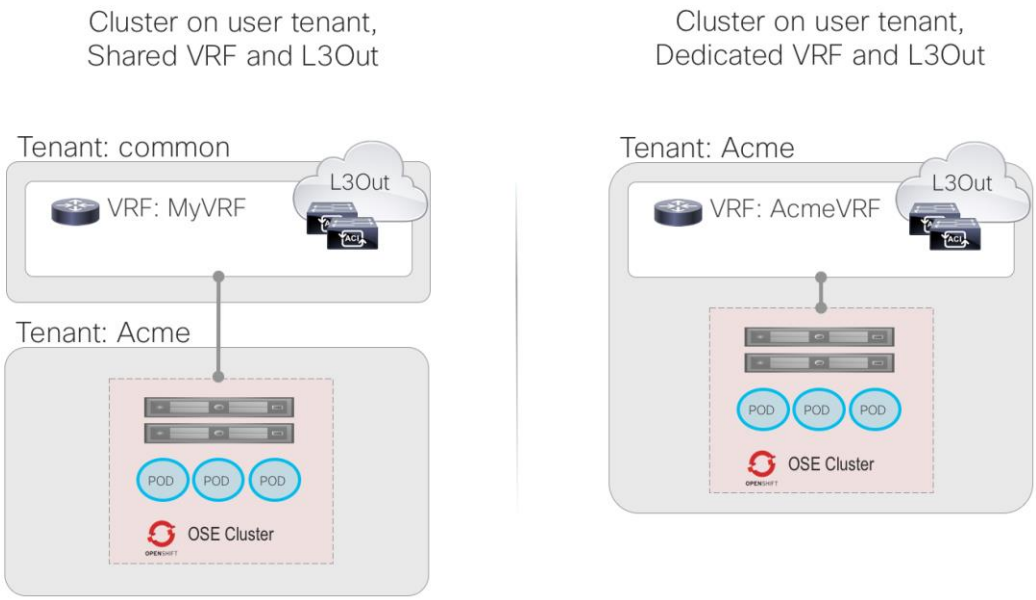

Figure 10: ACI CNI plugin tenancy options

The nodes of an OpenShift cluster represent two types of endpoints for the ACI fabric: host endpoints and Pod endpoints.

1. OpenShift nodes require connectivity between them to allow the cluster to function. This includes traffic such as the Kubernetes API, etcd, storage, access to repositories, and node management or administration which runs on the node host IP address.
2. Pods that run on each of the nodes require connectivity for arbitrary applications they may implement. In some cases, these Pods are part of the OpenShift cluster infrastructure. For instance, the integrated docker registry, the web console, the service catalog, or Prometheus are examples of Pods dedicated to OpenShift cluster infrastructure. In most cases though, the Pods run applications in one or more user projects/namespaces.

A basic premise of Kubernetes networking is that the Pod IP addresses must be reachable from the host IP addresses. Features like Pod health monitoring which are key to auto scaling capabilities rely on the OpenShift nodes to be able to reach the Pods. The following table summarizes the connectivity requirements of the elements involved in an OpenShift cluster.

Type of Endpoint	Node	Pod	External
Node	Kube-API, etcd, storage, etc.	Health-checks, remote shell, etc.	Red Hat Repositories, Docker Registry, storage, Logging
Pod	DNS	Applications, Monitoring, etc.	GitHub,
External	Admin, API, Web Console	Applications	

Table 2

The Cisco ACI CNI plugin allows administrators to deploy multiple OpenShift clusters, each running its own instance of the plugin, to a single ACI fabric or APIC cluster. In the case of deploying multiple OpenShift Clusters, each one has its own VMM Domain and must be deployed to a different ACI tenant.

OpenShift nodes must be connected to fabric leaf switches. When running OpenShift baremetal nodes, these connections typically happen via virtual port channels. Corresponding Linux bond interfaces provide network connectivity and redundancy. When running on virtualized nested environments, OpenShift nodes running as Virtual Machines connect to the ACI leaf switches over Layer 2 via the supported hypervisor's virtual switch. At the time of this writing, this can be either VMware vSphere VDS or Red Hat OpenStack Open vSwitch.

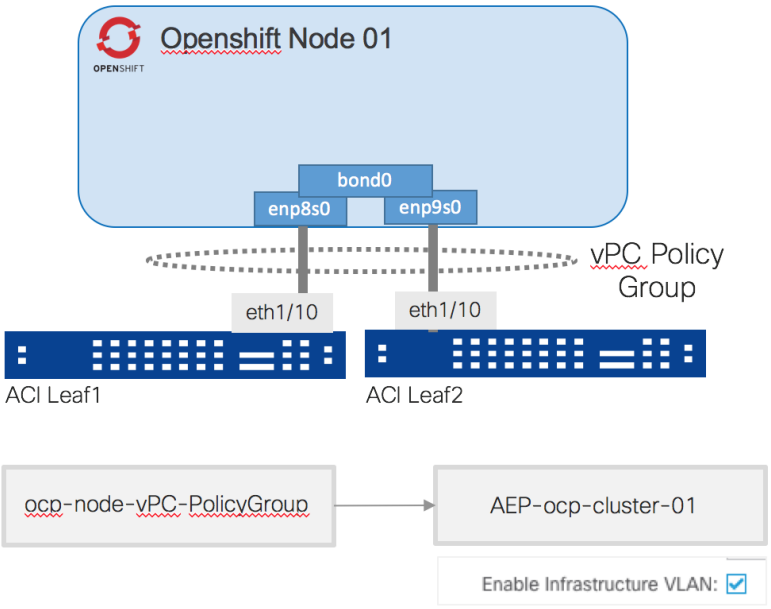

Figure 11: Connecting OpenShift nodes to ACI

Apart from the interface configuration, there are various other configuration elements required on ACI to enable OpenShift clusters to function. The connectivity requirements of the OpenShift clusters specified in Table 5.1 above are served via an ACI Application Profile in the ACI tenant selected for the cluster. By default, the acc-provision tool found on cisco.com creates at the time of installation a tenant, a VMM domain, a "Kubernetes" Application Profile with an EPG for nodes and Pods that are used to allow the cluster connectivity. Please refer to the installation guide for details on how to use this tool. Following we describe all the fabric elements required, explaining which ones are created by the tool and which ones require day-0 fabric configuration:

- **Attachable Entity Profile (AEP)**: the AEP objects group servers with similar connectivity requirements. AEP objects are associated to the interfaces that connect to those servers. For instance, an AEP may be dedicated to identify a group of servers running a specific hypervisor that is part of a given cluster. AEP objects are further associated with Domains in ACI. Each AEP can be associated to multiple domains. When deploying OpenShift in bare metal nodes, the AEP is associated with the interface Policy Groups connecting to OpenShift. In case of nested deployments, the Cisco ACI CNI plugin references the AEP of the VMM where the OpenShift Cluster is nested. In any case, the AEP must have the ACI Infrastructure VLAN enabled as seen in Figure 11. The AEP object is not created by the `acc-provision tool`, therefore it

is part of the day-0 configuration performed by a fabric administrator or as part of the automation workflow used to set up a new cluster. You provide the name of the AEP to the acc-provision tool which then takes care of binding the appropriate domain(s) to the AEP, as well as creating VxLAN pools and static path bindings at the EPG level to ensure node to node connectivity.

- **OpenShift Cluster Physical Domain** (pdom). The physical domain profile stores the physical resources (ports and port-channels) and encapsulation resources (VLAN/VXLAN) that are used for endpoint groups associated with this domain. This domain is created by the acc-provision tool, named as <cluster-name>-pdom and associated with the indicated AEP. The domain also has an associated VLAN pool with the VLANs that are used for connecting nodes (`kubeapi_vlan` in the `acc-provision` tool configuration file) and external load balancer services (`service_vlan` in the `acc-provision` tool configuration file).

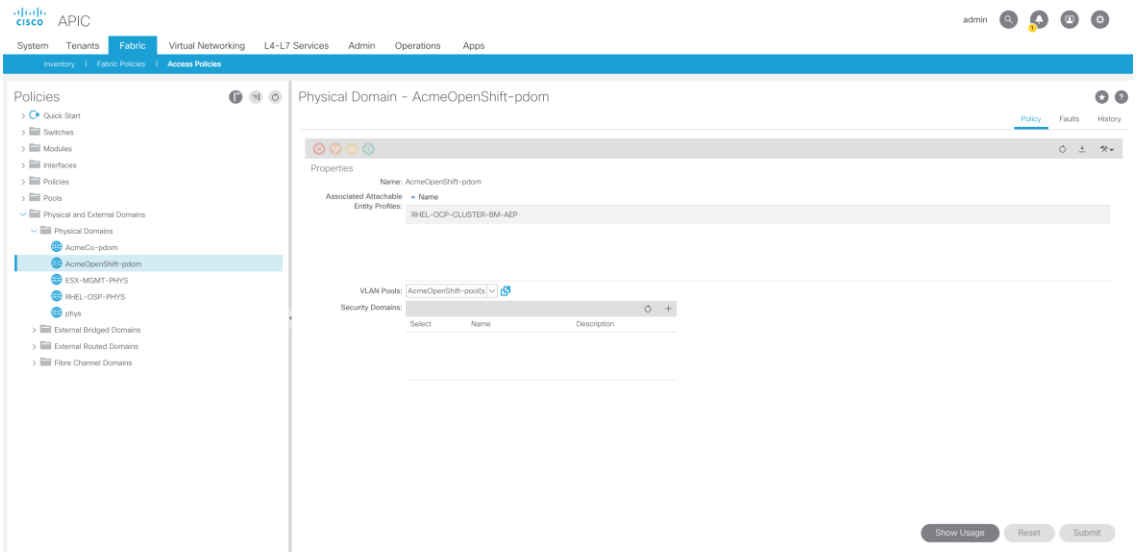

Figure 12: View of OpenShift VMM Domain in APIC

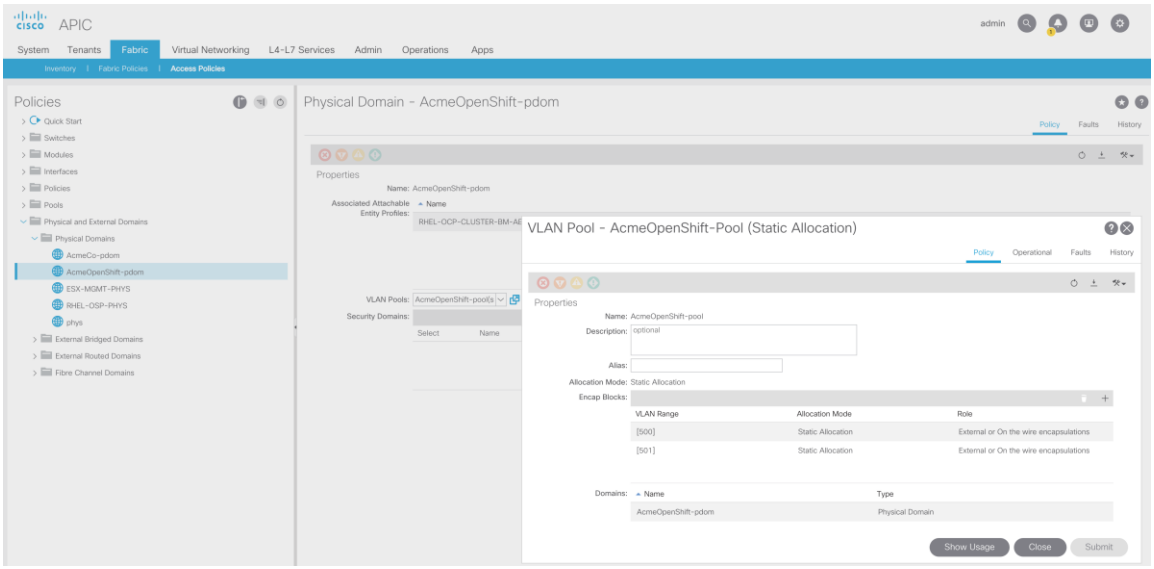

Figure 13: VLAN pools used by OpenShift VMM domain

- **OpenShift Cluster VMM Domain** (vmmdom): the VMM domain helps APIC dynamically learn about new endpoints that are connected to the fabric via a managed virtual switch, in this case, the Opflex-managed Open vSwitch. The VMM Domain is named as per the tenant where the cluster is deployed. It has a multicast pool and optionally a VLAN pool associated, if the CNI plugin is configured to use VLANs instead of VXLAN.

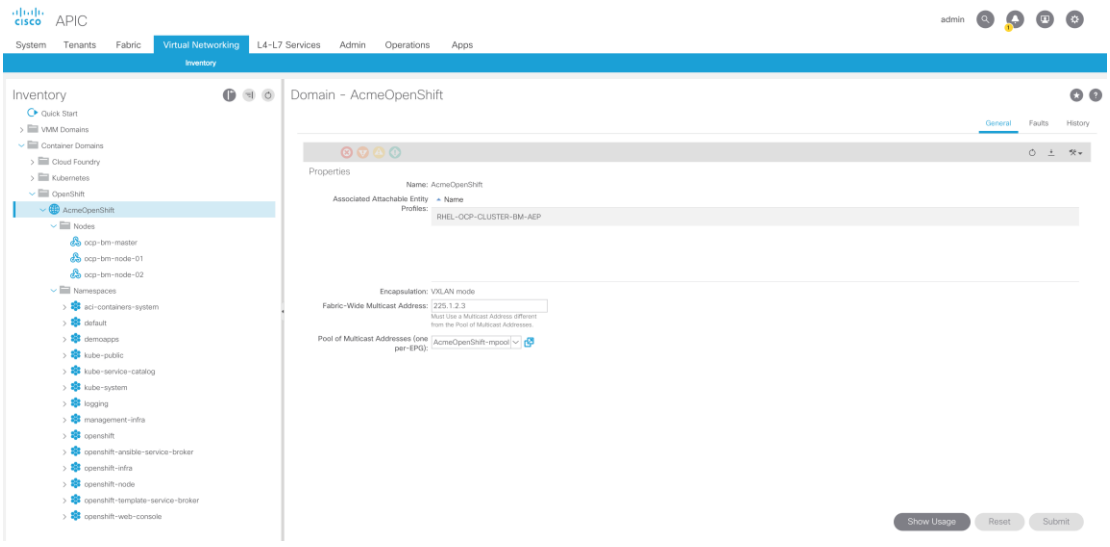

Figure 14: View of OpenShift VMM Domain showing namespaces

- **Tenant**: as mentioned before, when building an OpenShift cluster connected to ACI using the Cisco ACI CNI Plugin, the cluster must be associated with an ACI tenant. The

cluster can be deployed to a new tenant or to an existing one. If the tenant specified does not exists, the `acc-provisioning` tool creates it.

- **VRF**: this is the routing domain that is used for the subnets of the OpenShift Cluster endpoints, both node and Pod addresses. This object is not created by the `acc-provisioning` tool. It can be created on the cluster tenant or else on the common tenant.
- **L3Out Interface and associated External EPG(s):** this is the interface used for communication between the OpenShift cluster any and endpoints not connected directly to the fabric. This interface and at least one External EPG must be created in the selected VRF as part of the day-0 configuration. The ACI CNI plugin may create additional external EPGs on this L3Out interface during normal cluster operation for exposed external OpenShift services. You provide the name of the L3Out and an external EPG to acc-provision which then creates the appropriate contracts between Pods EPGs and the L3Out EPG.
- **Bridge Domains:** Bridge Domains are L2 constructs with associated subnets that belong to a VRF. They are implemented as distributed Switch Virtual Interfaces (SVI) that are automatically configured as required on the ACI fabric. For the Cisco ACI CNI plugin to function, three Bridge Domains (BDs) are required and configured by the `acc-provision`:
    - **kube-node-bd** is configured on the tenant selected to deploy the OpenShift cluster. It is associated to the same VRF used for the L3Out. This can be a VRF that exists in the cluster tenant, or else on the common tenant. The BD is automatically associated to the L3Out interface. This BD is configured with the subnet used to assign host IP addresses to the OpenShift cluster nodes.
    - **kube-pod-bd** is also configured on the tenant of the OpenShift cluster and it is associated with the same VRF of the L3Out. This BD is not associated to the L3Out by default. If it is required for Pods to access external fabric addresses, it is necessary to associate the BD to the L3Out (via GUI, CLI, Ansible Playbook, etc.). One example where this is required is if Pods require accessing Github repositories.
    - **bd-kubernetes-service** is different from the previous two. This BD is created in the tenant where the L3Out exists. This means that if using a shared L3Out in common tenant, this BD is created in tenant common. This BD is not created by the acc-provision-tool but does not require an administrator to create it. Instead, it is created by the `aci-containers-controller` when it comes

oline. This BD has a subnet internally used for the two-stage PBR load balancing feature.

- **Kubernetes Application Profile**. An Application Profile is a collection of Endpoint Groups (EPG) and their communication policies specified using ACI Contracts. The Kubernetes Application Profile enables connectivity for all nodes and Pods in the OpenShift cluster and is created by the `acc-provision` tool in the tenant selected for the cluster. The Application Profile includes the following objects:
  - **kube-nodes EPG**. This EPG connects the host IP address of the nodes of the OpenShift cluster and is associated to the kube-node-bd Bridged Domain. It is mapped to the Physical Domain created by acc-provision tool by associating it at the AEP level, so static path bindings are not required when adding new nodes to the cluster.
  - **kube-default EPG**. This EPG is mapped to the OpenShift cluster VMM domain and associated to the kube-pod-bd Bridge Domain. By default, all Pods launched in the OpenShift cluster is connected to this EPG, unless they are annotated for the plugin to do otherwise.
  - **kube-system EPG**. This EPG is also mapped to the OpenShift cluster VMM domain and associated to the kube-pod-bd Bridge Domain. All Pods on the kube-system namespace are placed on this EPG. Note that this EPG is only used for pure Kubernetes deployments, it has no relevance in OpenShift deployments.
  - **Contracts**. In ACI, contracts define security policies that implement filters that control what communications are allowed. By default ACI implements a white-list policy model, so only communications explicitly define are enabled between different EPGs. For OpenShift to function, various type of traffic must be allowed, such as DNS, kube-api, health-checks, etcd, etc. The `acc-provision` tool creates basic contracts to enable the cluster to function.

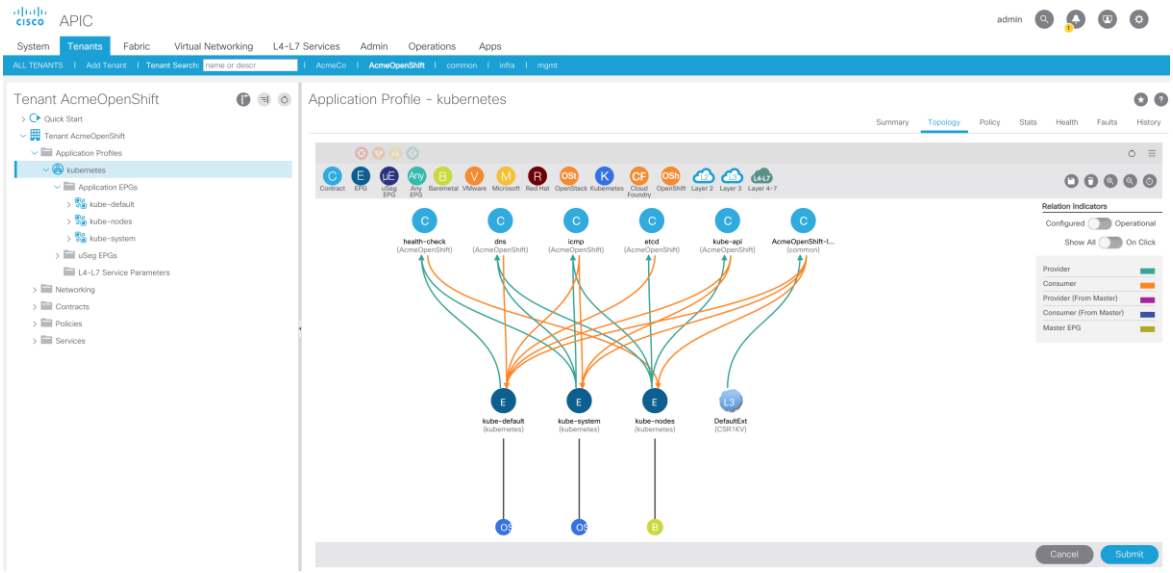

Figure 15: ACI Kubernetes Application Profile

- **Cluster L4-7 Device**. The Cisco ACI CNI Plugin provides a cloud controller implementation to leverage the ACI fabric for L4 load balancing for external LoadBalancer services. Each OpenShift cluster is represented as a Logical Load Balancer and has an associated Service Graph template that leverages Cisco ACI Policy Based Redirection (PBR) capabilities. The the `acc-provision` tool creates the device and Service Graph template on the tenant that owns the VRF and L3Out.

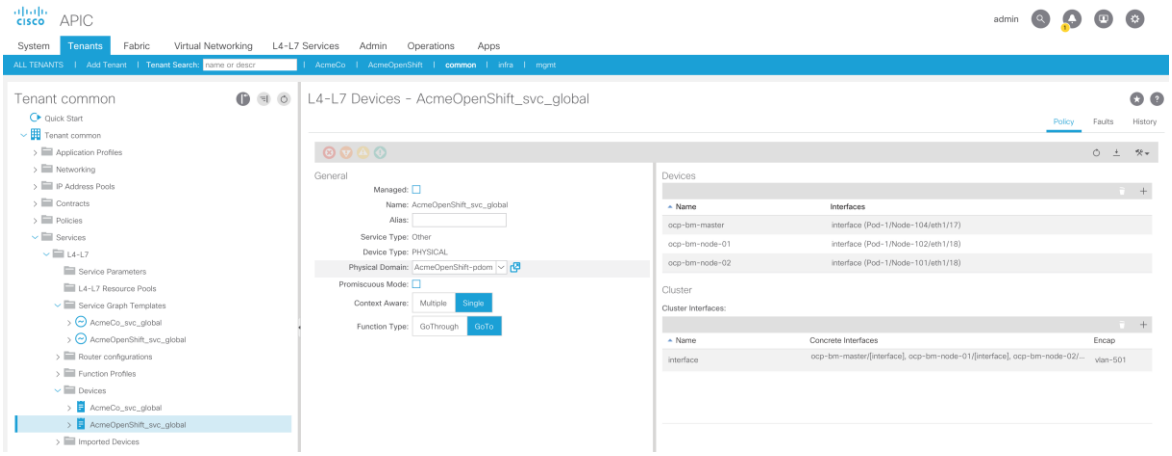

Figure 16: ACI Logical L4 Load Balancer for OpenShift cluster

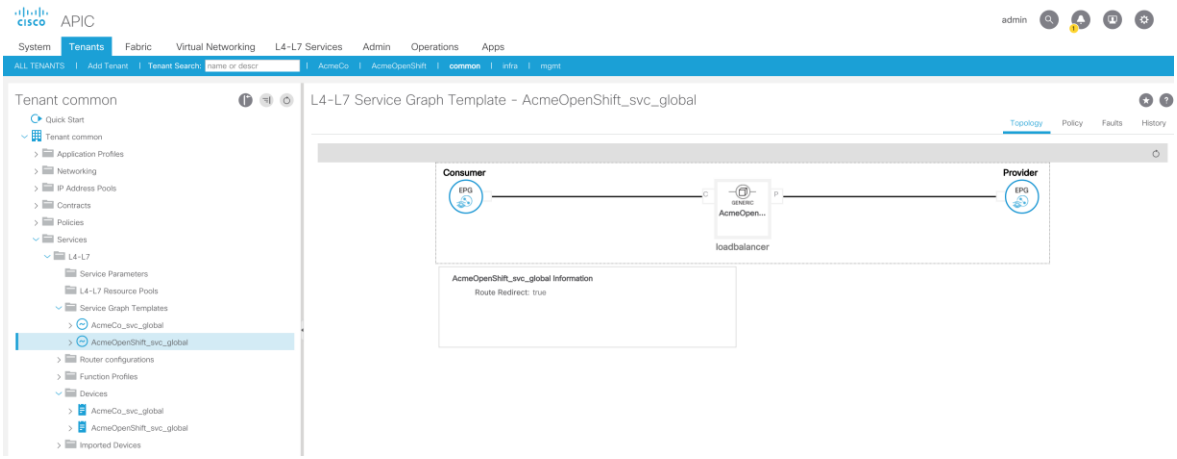

Figure 17: ACI Logical L4 Load Balancer Service Graph Template for OpenShift cluster

The acc-provision tool creates only the basic three EPGs and contracts required for basic operation of an OpenShift cluster. It is possible that additional EPGs and contracts are required. For instance, if the OpenShift cluster uses the Service Catalog, it is necessary to add additional configuration to the Kubernetes application in order to allow the kube-default EPG to consume the etcd contract that allows tcp/2379. You need a contract to the OpenShift ingress router.

The following graphic illustrates the various components once deployed, showing a single OpenShift master and single node. For illustration purposes, we show the OpenShift router Pod on the first node and the registry Pod on the master. In both cases, they are connected to the kube-default EPG, extended to Open vSwitch by means of OpFlex. The aci-containers-controller Pod is shown running on the node. Both master and node run aci-containers-host and aci-containers-openvswitch (the name has been abbreviated for illustration purposes).

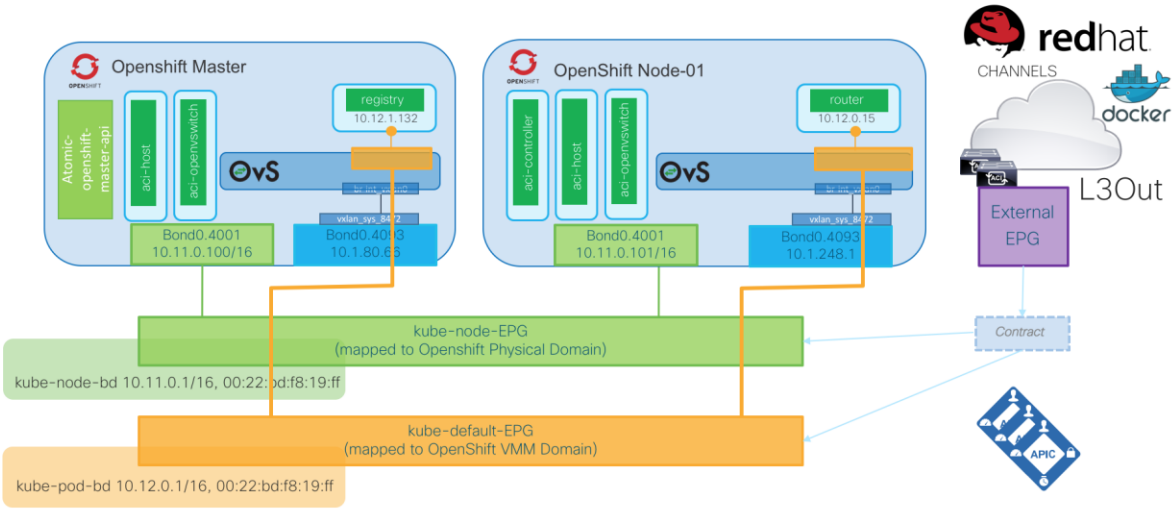

Figure 18: Diagram view of nodes with ACI CNI plugin and EPG model

Similarly, for illustration purposes, the following figure shows the ACI containers running on the aci-containers-system OpenShift project as seen on the OpenShift CLI and on the Web Console for a system with two nodes and one master.

```
[root@ocp-bm-master ~]# oc get pods -o wide
NAME                                       READY     STATUS    RESTARTS   AGE       IP             NODE
aci-containers-controller-65cfd66d5d-28vtx 1/1       Running   0          4d        10.11.0.100    ocp-bm-master
aci-containers-host-pdhvv                  3/3       Running   0          4d        10.11.0.100    ocp-bm-master
aci-containers-host-vrvxv                  3/3       Running   0          4d        10.11.0.101    ocp-bm-node-01
aci-containers-host-wjgxp                  3/3       Running   0          4d        10.11.0.102    ocp-bm-node-02
aci-containers-openvswitch-65vlg           1/1       Running   0          4d        10.11.0.100    ocp-bm-master
aci-containers-openvswitch-fln5r           1/1       Running   0          4d        10.11.0.102    ocp-bm-node-02
aci-containers-openvswitch-nfpps           1/1       Running   0          4d        10.11.0.101    ocp-bm-node-01
[root@ocp-bm-master ~]#
```

Figure 19: ACI CNI plugin containers as seen on the 'oc' CLI

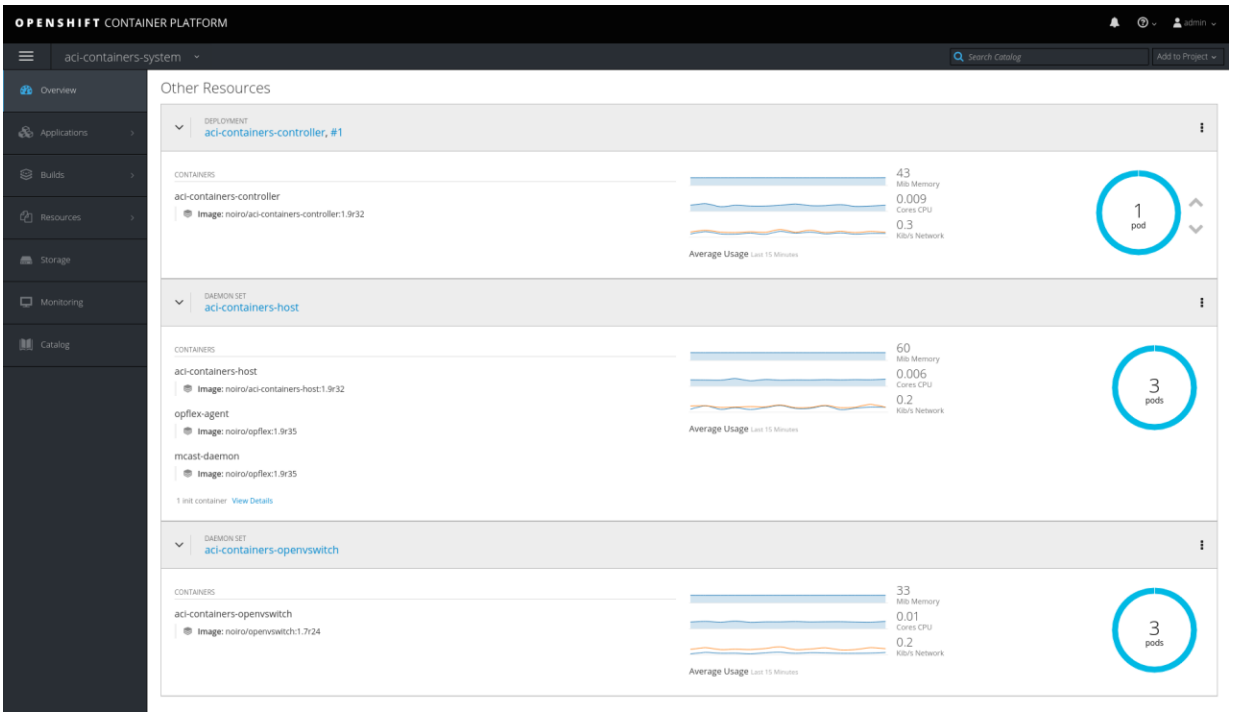

Figure 20: ACI CNI plugin containers as seen on the Web Console

5.3. Managing the address spaces for the ACI CNI Plugin

A working OpenShift cluster requires IP addresses for various functions. Every node requires at least one IP address for the host TCP/IP stack that is used for running the API, accessing repositories, registries, etc. It is possible that an additional interface and IP is used for Out-of-Band Management. Then, the cluster needs to be able to assign IP addresses to Pods, internal services and external services. Prior to the OpenShift cluster installation, it is important to conduct IP address planning and decide which subnets or Classless Inter-Domain Routing (CIDR) address spaces are used for various functions.

When using the Cisco ACI CNI plugin, the IP addresses for Pods and services are provided by the plugin and in general all subnets must be configured in the fabric.

The following table summarizes the various subnets or CIDRs required, including the parameter used by the OpenShift installer to refer to them and the corresponding Cisco ACI CNI plugin parameter and associated fabric configuration.

OpenShift Install Parameter	ACI Plugin Parameter	Fabric Configuration
osm_cluster_network_cidr This is the network from which pod IPs are assigned. This network block should be a private block and must not conflict with existing network blocks in your infrastructure to which pods, nodes, or the master may require access.	**pod_subnet**	This subnet is configured under kube-pod-bd Bridge Domain.
OpenShift_portal_net This variable configures the subnet in which internal services are created within the OpenShift Container Platform. This network block should be private and must not conflict with any existing network blocks in your infrastructure to which pods, nodes, or the master may require access to, or the installation will fail. This value overrides the ACI CNI plugin parameter.	n/a	This subnet is not configured on the fabric, nor is visible at the leaf level. It is used only on Opflex-OVS configurations for ClusterIP load balancing.
OpenShift_master_ingress_ip_network_cidr For OpenShift, the external IP used for the LoadBalancer service type is automatically chosen from the subnet pool specified in the igressIPNetworkCIDR configuration in the /etc/origin/master/master-config.yaml file. This subnet should match the extern_dynamic property configured in the input file provided to acc_provision script. If a specific IP is desired from this subnet pool, it can be assigned to the "loadBalancerIP" property in the LoadBalancer service spec. For more details refer to OpenShift documentation here: https://docs.openshift.com/container-platform/3.9/admin_guide/tcp_ingress_external_ports.html#unique-external-ips-ingress-traffic-configure-cluster	**extern_dynamic**	This subnet is not configured under any BD. Endpoints from this subnet are configured under external EPGs.
OpenShift_master_external_ip_network_cidrs ExternalIPNetworkCIDRs controls what values are acceptable for the service external IP field but do not work with type LoadBalancer. See https://kubernetes.io/docs/concepts/services-networking/service/#external-ips	**extern_static**	The extern_static parameter in acc-provision is not used in OpenShift.

Table 3

Be aware that the IP range you pick for Pods should be routable within your organization. ACI does not perform source NAT when Pods are egressing the fabric. Pods egress the fabric using their assigned IP address directly. You can attach a NAT router to the ACI L3Out of course, but keep in mind NAT is not a function provided by ACI natively. Plan accordingly.

Once deployed and running, the configuration for the Cisco ACI CNI plugin for Red Hat OpenShift is kept on a configmap object in the aci-containers-system project. This object keeps track of the APIC IP addresses, the user account and key used to communicate with APIC, the subnets used for Pods and services, etc. In other words, the container controller is said to be stateless.

5.4. Cisco ACI CNI Plugin Feature Deep-Dive

The Cisco ACI CNI Plugin provides all networking and security requirements for the OpenShift cluster. When using the Cisco ACI CNI plugin there is no need to use egress routers, however ingress routers to expose routes (Layer 7 Load Balancing) are still required.

The key features of the Cisco ACI CNI Plugin are:

- IP Address Management and Virtual Networking for Pods and Services
- Distributed Routing and Switching with integrated VXLAN overlays implemented fabric-wide and on Open vSwitch
- Distributed Load Balancing for ClusterIP services
- Hardware-accelerated Load Balancing for LoadBalancer services
- Distributed firewall for implementing Network Policies
- EPG-level segmentation for Kubernetes objects using annotations
- Consolidated visibility of Kubernetes networking via APIC VMM Integration

In this section, we explain in detail how each functionality enabled by the ACI CNI Plugin for Red Hat OpenShift works.

5.4.1. IP Address Management and Virtual Networking for Pods and Services

A basic responsibility of the CNI plugin is to create the interfaces on the Pods, connect them to a virtual network on the host and assign the Pod's interface an IP address as well as configure it with the necessary routes. In the case of the Cisco ACI CNI plugin, the default route on the Pods points to the distributed default gateway provided by the ACI fabric on the kube-node-bd Bridge Domain.

The IPAM configuration for the ACI CNI plugin is dictated by the configuration files placed on /etc/cni/net.d/10-opflex-cni.conf. When using the Cisco ACI CNI plugin, this file is present on each node and looks as follows:

```
[root@ocp-bm-master ~]# cat /etc/cni/net.d/10-opflex-cni.conf
{
   "cniVersion": "0.3.1",
   "supportedVersions": [ "0.3.0", "0.3.1" ],
   "name": "k8s-pod-network",
   "type": "opflex-agent-cni",
   "ipam": {"type": "opflex-agent-cni-ipam"}
}
[root@ocp-bm-master ~]#
```

Figure 21

The network type for Pods is set to 'opflex-agent-cni' and specifies the binary that must be executed when required. The 'ipam' to be used for the Pods is set to be done by the 'opflex-agent-cni-ipam'.

Each OpenShift node has one or more ranges of IP addresses assigned from the `pod_subnet` (`osm_cluster_network_cidr`) CIDR available for the opflex agent running on the node. The agent assigns IP addresses for Pods from these ranges. This can be seen on the opflex annotations of the node, as shown below for the first two nodes (ocp-bm-node-01 and ocp-bm-node-02) of a cluster where `osm_cluster_network_cidr = 10.12.0.0/16`:

```
[root@ocp-bm-master ~]# oc describe node ocp-bm-node-01 | grep opflex
Annotations:        opflex.cisco.com/pod-network-ranges={"V4":[{"start":"10.12.0.2","end":"10.12.0.129"}]}
                    opflex.cisco.com/service-endpoint={"mac":"58:AC:78:9F:4F:F0","ipv4":"10.15.0.3"}
[root@ocp-bm-master ~]# oc describe node ocp-bm-node-02 | grep opflex
Annotations:        opflex.cisco.com/pod-network-ranges={"V4":[{"start":"10.12.1.2","end":"10.12.1.129"}]}
                    opflex.cisco.com/service-endpoint={"mac":"58:AC:78:9F:4F:F1","ipv4":"10.15.0.2"}
[root@ocp-bm-master ~]# _
```

Figure 22: Opflex Pod network CIDR for two OpenShift nodes

We can see on the image in Figure 21 that ocp-bm-node-01 assigns IP addresses from the range 10.12.0.2-10.12.0.129, and ocp-bm-node-02 instead uses 10.12.1.2-10.12.1.129. If a node uses all its available Pod address space, a new range is allocated from the cluster's Pod CIDR. As of the latest code, we now use smaller chunks (32 IP per chunk). For example, {"start":"10.33.0.2","end":"10.33.0.33"} allows you to use a /24 as a POD subnet in a smaller environment.

Apart from the common CNI configuration files, the Cisco ACI CNI plugin maintains much of its configuration on a Kubernetes 'configmap' object in the aci-containers-systems project. Below, we can see a partial snippet of this configmap where we highlight the networking configuration for the cluster:

When a new Pod is launched, the OpenShift cluster scheduler allocated it to runs on a given OpenShift node. The kubelet running in the OpenShift-atomic-node invokes the CNI plugin binay opflex-agent-cni on the node to get the required networking. When the opflex-agent-cni plugin is invoked, the agent creates the virtual Ethernet interface on the Pod and on Open vSwitch, picks a free random IP address from the node's IP address range for Pods as explained previously, and configures the Pod's interface with that IP address, sets the default route to point to the fabric's distributed gateway (the Pod BD on the leaf the node is attached to) and configures the right DNS server on /etc/resolv.conf.

To illustrate this process once completed, we show an example below for a Pod running the NGINX web server image. A Pod has been allocated to run on node ocp-bm-node-01 and the plugin has chosen the IP address 10.12.0.13/16 from the node's IP range. Notice that the subnet mask used is the cluster's subnet, but the IP address is chosen from the range of the node. We can also see a screenshot from a shell running on the Pod using the 'oc rsh' command to show the Pod's routing table configured with a default route pointing to the 10.12.0.1 IP address, which corresponds to a distributed gateway on the ACI fabric, configured under the kube-node-bd. Finally, we see that the Pod is connected to a virtual Ethernet interface (veth483acb1f) on an Open vSwitch Bridge.

```
[root@ocp-bm-master ~]# oc describe configmap aci-containers-config
Name:         aci-containers-config
Namespace:    aci-containers-system
Labels:       aci-containers-config-version=dc99d4af-381e-41de-ba76-
504421e0e94b
              network-plugin=aci-containers
Annotations:  kubectl.kubernetes.io/last-applied-
configuration={"apiVersion":"v1","data":{"controller-config":"{
\n    \"log-level\": \"info\",\n    \"apic-hosts\": [\n
\"10.48.169.10\",\n        \"10.48.169....

[truncated output]

host-agent-config:
----
{
    "log-level": "info",
    "aci-vmm-type": "OpenShift",
    "aci-vmm-domain": "AcmeOpenShift",
    "aci-vmm-controller": "AcmeOpenShift",
    "aci-vrf": "default",
    "aci-vrf-tenant": "common",
    "service-vlan": 501,
    "encap-type": "vxlan",
    "aci-infra-vlan": 4093,
    "cni-netconfig": [
        {
            "gateway": "10.12.0.1",
            "routes": [
                {
                    "dst": "0.0.0.0/0",
                    "gw": "10.12.0.1"
                }
            ],
            "subnet": "10.12.0.0/16"
        }
    ]
}
```

Figure 23

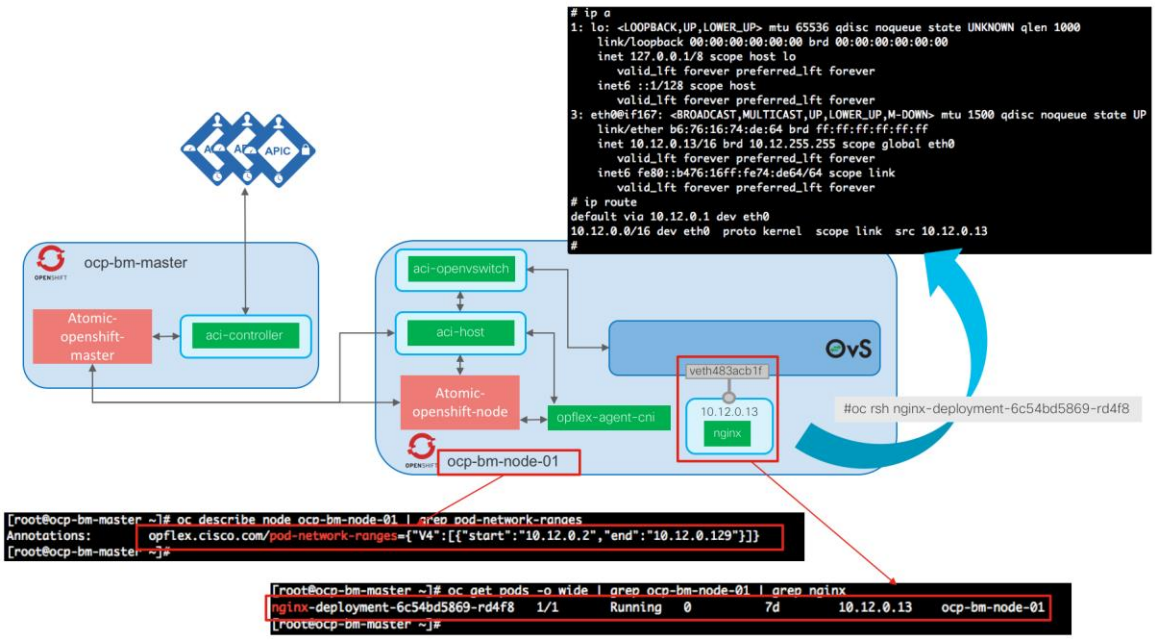

Figure 24: Pod IP Address Management example when using ACI CNI plugin

When a Pod is destroyed, its IP address is released and returned to the node's pool and can be reused for other Pods in the future.

The ACI CNI plugin also provides IP address management for service and Load Balancer IPs.

5.4.2. Overlays Implemented Fabric Wide and on Open vSwitch

Apart from IP address management, Pods require connectivity to other Pods in the Cluster as well as potentially to external endpoints. External endpoints may be directly connected to the ACI fabric, such as Virtual Machines, Bare Metal servers or Pods from other clusters, or may not be connected to the fabric, such as repositories, registries, etc.

When using the Cisco ACI CNI plugin, the ACI fabric provides distributed routing and switching for all connectivity required for Pods. Every Pod becomes an endpoint in the Cisco ACI fabric, connected to the integrated VXLAN overlay and part of a given VRF. In the case of Pods, Cisco ACI provides routing and switching for Pods not only on the fabric's physical switches, but also on the OpenShift node's Open vSwitch, which effectively acts as a virtual leaf.

But APIC does not need to program Open vSwitch directly. Instead, this task is delegated to the opflex agent running on the node. The opflex agent learns information about the Pod from the CNI integration with the OpenShift node, and queries the upstream ACI leaf to learn the fabric required policy configuration, including the EPG, the VRF, and other information. The opflex agent maintains an endpoint file in /var/lib/opflex-agent-ovs/endpoints for each Pod. This file contains the information required to connect the Pod to the ACI integrated overlay. We can see below the EP file for the NGINX Pod of the example in Figure 23.

```
[root@ocp-bm-node-01 endpoints]# cat 2880e06d-e100-11e8-9cf3-
58ac789f6ffa_755137d9dac5144002017ef84dffd526f4252b54949d30785d51f5457822
a850_veth483acb1f.ep
{
  "uuid": "2880e06d-e100-11e8-9cf3-
58ac789f6ffa_755137d9dac5144002017ef84dffd526f4252b54949d30785d51f5457822
a850_veth483acb1f",
  "eg-policy-space": "AcmeOpenShift",
  "endpoint-group-name": "kubernetes|kube-default",
  "ip": [
    "10.12.0.13"
  ],
  "mac": "b6:76:16:74:de:64",
  "access-interface": "veth483acb1f",
  "access-uplink-interface": "pa-veth483acb1f",
  "interface-name": "pi-veth483acb1f",
  "attributes": {
    "app": "nginx",
    "interface-name": "veth483acb1f",
    "namespace": "default",
    "pod-template-hash": "2710681425",
    "vm-name": "nginx-deployment-6c54bd5869-rd4f8"
  }
```

Figure 25

The EP file contains all relevant information to correctly configure Open vSwitch to provide connectivity to the Pod. In particular, as seen in Figure 25, the opflex agent learns to which EPG the Pod must be connected.

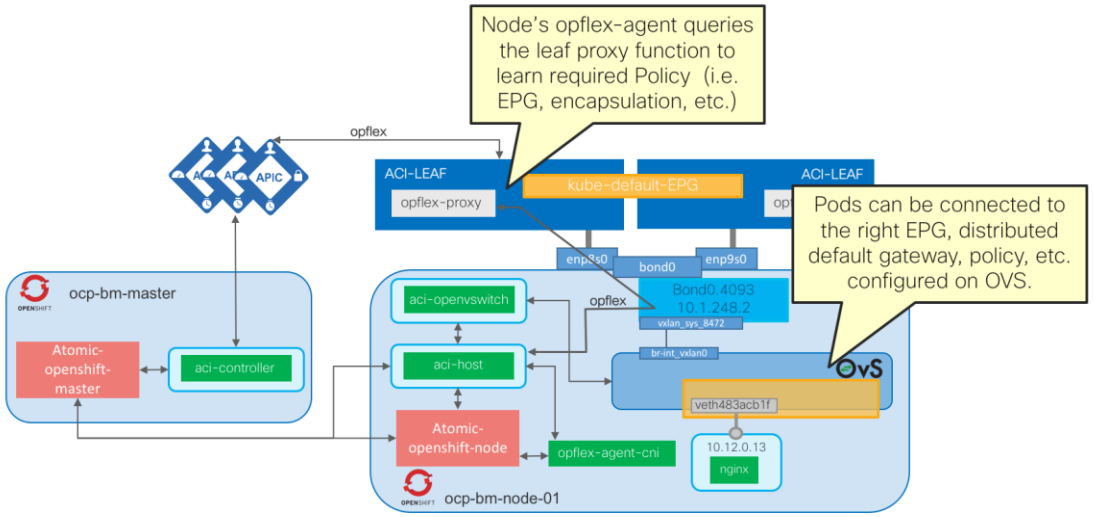

Figure 26: Representation of the opflex agent and opflex proxy function

This model effectively extends the fabric routing and switching capabilities to the Open vSwitch of the node. In Figure 26, we see a second Pod running the busybox image that has been scheduled to the same node as our nginx Pod from previous examples. Connections between these two Pods are switched locally on the Open vSwitch, minimizing latency.

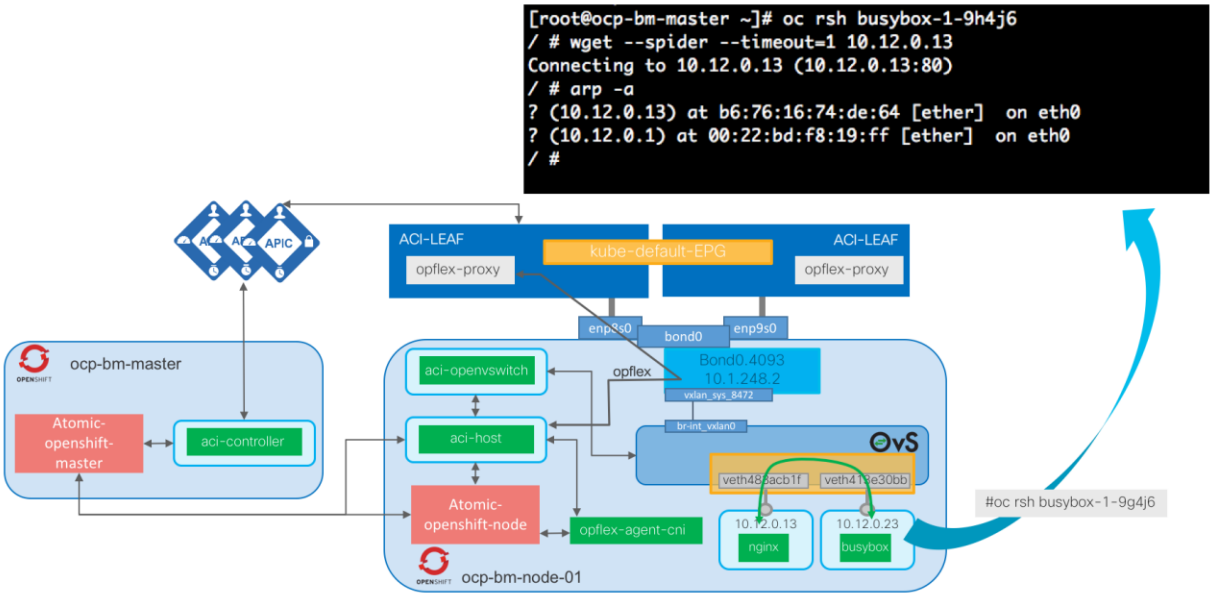

Figure 27: Local switching between Pods on the same node

The first hop for routing or switching decisions for a Pod's traffic is at the Open vSwitch of the node. When traffic is not destined to a Pod local to the node, the traffic is encapsulated with the Pod's EPG encapsulation details, which can be a VLAN or VXLAN encapsulation (per the configuration provided to acc-provision), and sent to the destination. Figure 27 shows the example where the busybox Pod is located on another node and traffic is traversing the physical fabric.

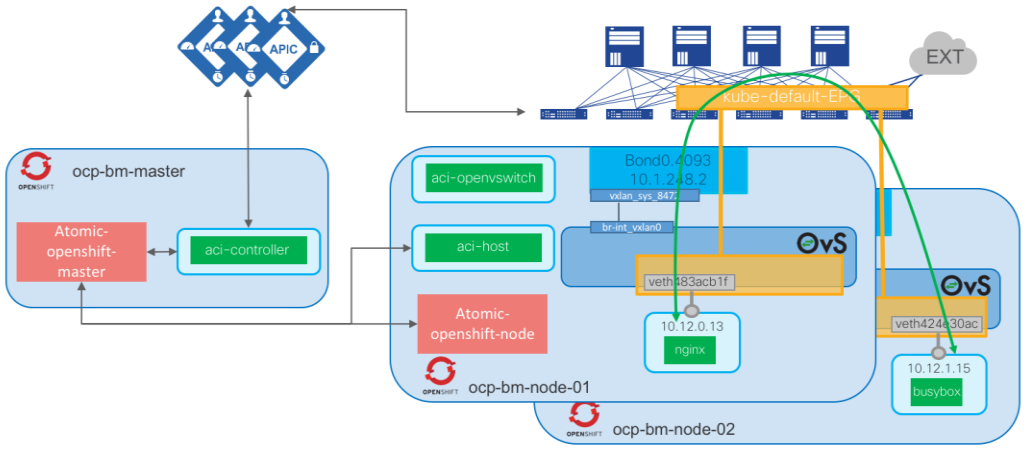

Figure 28: Fabric switching between Pods on the different nodes

Routing to any subnet connected to the ACI fabric follows the same path from Figure 27, of course assuming that traffic between different EPGs is allowed by having the appropriate ACI contracts configured (such contracts are enforced by ACI in the Open vSwitch and in the ACI leaf, as explained later in the document).

Routing to subnets external to the fabric is taken care of by ACI via L3Out interfaces. For the ACI fabric to route traffic between local subnets and external prefixes reachable via an L3Out interface, three things must be true:

- The Bridge Domain where the subnet is configured must be associated with the L3Out interface used to reach a given prefix.
- The subnet configuration must have the flag "advertise externally" configured.
- There must be a contract between an EPG associated with the Bridge Domain and an external EPG associated with the L3Out interface.

While the kube-node-bd is automatically associated to the L3Out used for the OpenShift cluster at the time of running the `acc-provision` tool, kube-pod-bd is not. Similarly, the kube-pod CIDR used to configure the Pod subnet is by default private to the VRF.

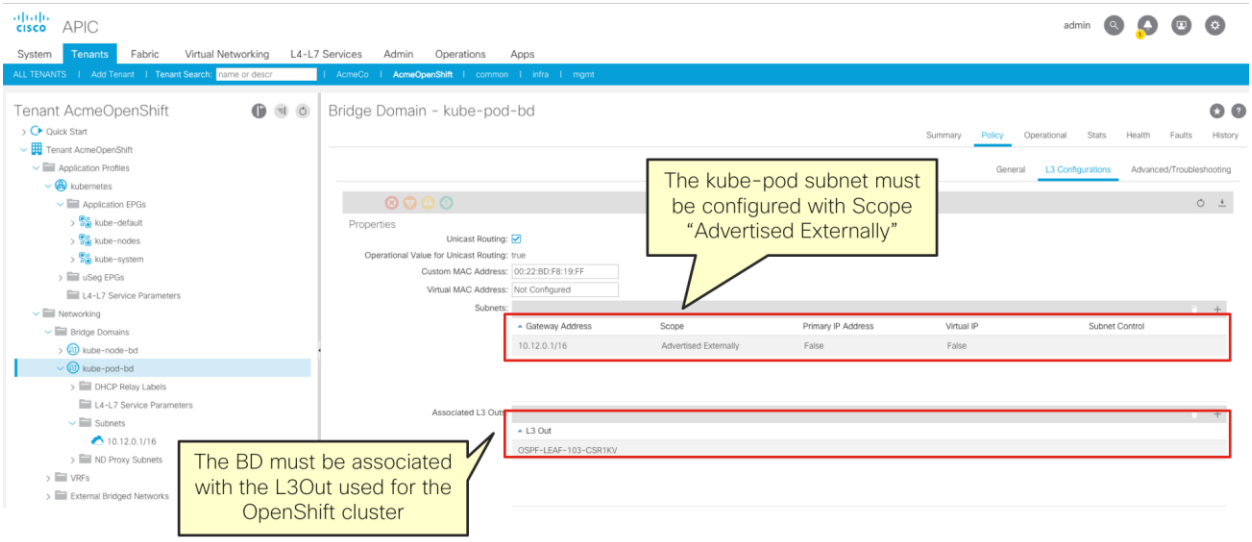

Figure 29: kube-pod-bd must be associated to the L3Out

If the Pods require access to external IP prefixes, the administrator must change the configurations for the kube-pod-bd and subnets as per Figure 28 in order to enable the subnet to be announced via the L3Out, assuming that it is configured to use dynamic routing. This is a very frequent use case because Pods often need to pull content from external repositories such as github. Once this is done, applications running on Pods can access external prefixes routing via the ACI fabric L3Out. In Figure 29 we show this at a high level where an application is accessing a Git service. Since it is very possible that the kube-pod CIDR is not routable outside of the ACI infrastructure, NAT for this IP range should be done at a router or firewall as shown in the figure below.

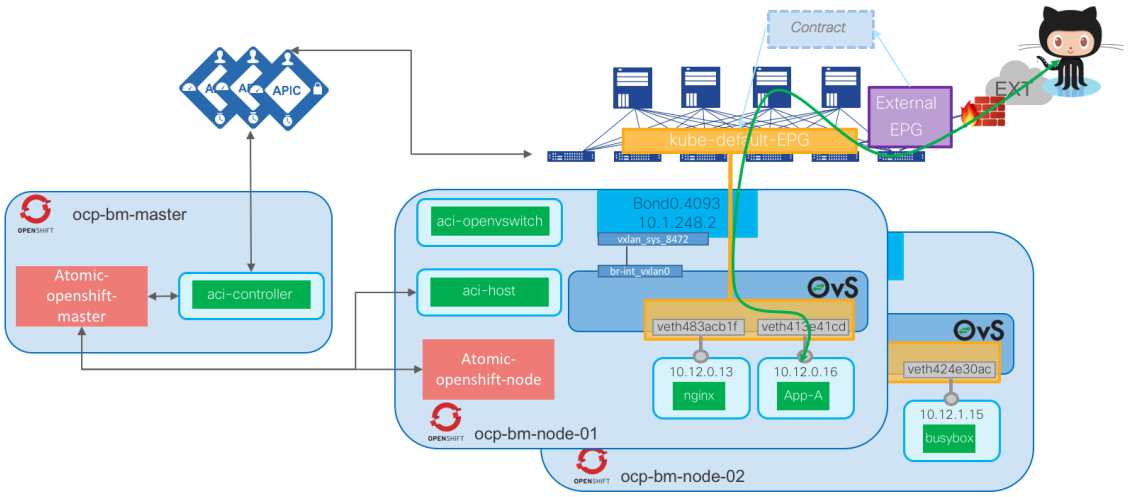

Figure 30: Pods accessing external resources via L3Out

5.4.3. Distributed Load Balancer for ClusterIP

Each Pod has a unique IP address, but Pods are meant to be ephemeral by nature, so you should not rely on the Pod's IP address to connect to a given application component or tier. Kubernetes provides 'service' objects to implement a persistent IP address to access a set of Pods. The Service object has an associated endpoint object that tracks the Pods that are backed by the service IP addresses, and therefore acts as an internal load balancer for traffic to those Pods. Essentially, the service object identifies a set of Pods in order to proxy connections towards them. The service object has an associated service endpoints list that contains an updated list of all the Pods that the service can send traffic to.

Services are assigned an IP address and port pair and use a label selector to find all the running containers that provide a certain network service on the given port. The most common type of service IP address is of type "ClusterIP". The ClusterIP is a persistent virtual IP address that is used for load balancing traffic internal to the cluster. This is usually considered East-West traffic, since it is traffic originating from Pods running in the cluster to the service IP backed by Pods that also run in the cluster. Traffic sent to the ClusterIP must be NAT'ed to the IP address of one of the Pods backing the service, which sees the traffic coming from the originating Pod.

The Cisco ACI CNI plugin for Red Hat OpenShift implements everything required for

service objects of type ClusterIP. When a new service object is created, the ACI CNI plugin assigns it an IP address from the `OpenShift_portal_net` CIDR. The plugin listens to the endpoint API and learns the list of Pods that are backed by the service. For example, we can see below an example for an NGINX service with three Pods as shown on the OpenShift Web Console:

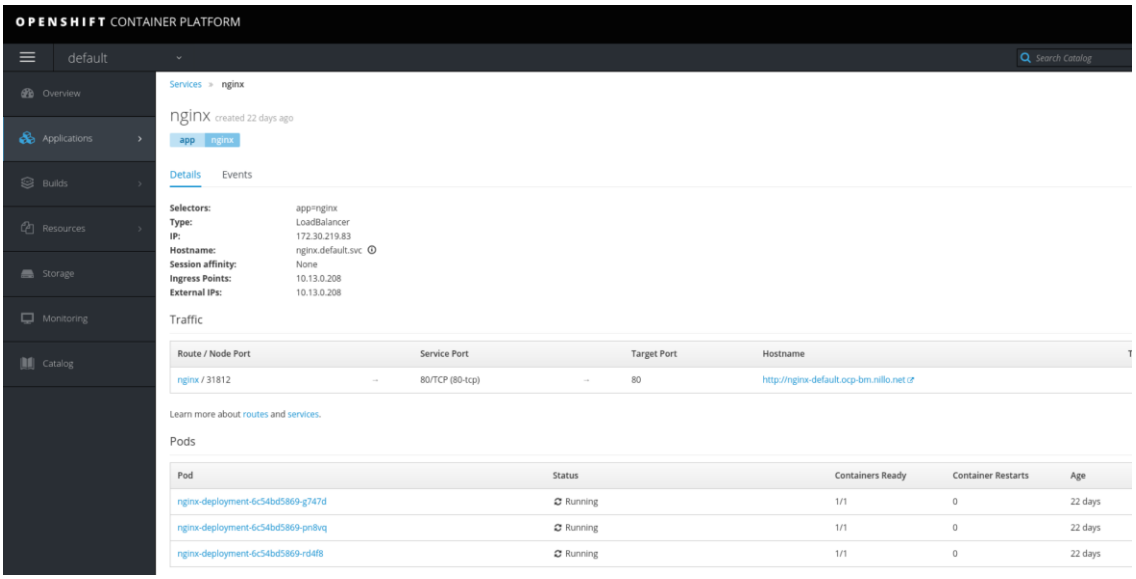

Figure 31: A view of a service from the Web Console

These endpoints correspond to Pods created by a Deployment controller and at any given time, the service may scale to extra or fewer endpoints either by an admin intervention or dynamically based on the service's load. We represent on Figure 31 the CLI output for the same NGINX service and backend endpoints and how this triggers the ACI CNI plugin to instruct the opflex agent to create a load balancer.

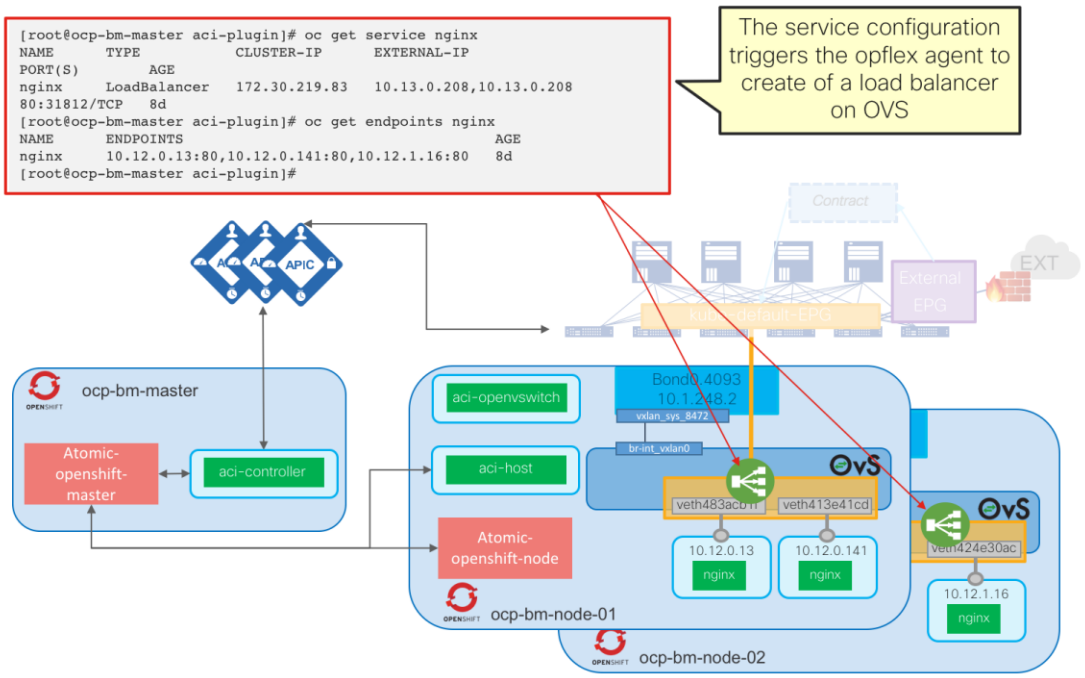

Figure 32: The APIC programs a distributed load balancer on OVS for ClusterIP

The plugin on every OpenShift node has access to all the required information and creates a service endpoint file under /var/lib/opflex-agent-ovs/services and configure openflow entries on the node's Open vSwitch that capture traffic for the service ClusterIP IP address and load balance it to the Pods that are backing the service. Below we can see an example of the service endpoint file for the same NGINX service of the example above.

```
[root@ocp-bm-master ~]# cat /var/lib/opflex-agent-ovs/services/2c5b7842-
e100-11e8-9cf3-58ac789f6ffa.service
{
  "uuid": "2c5b7842-e100-11e8-9cf3-58ac789f6ffa",
  "domain-policy-space": "common",
  "domain-name": "default",
  "service-mode": "loadbalancer",
  "service-mapping": [
    {
      "service-ip": "172.30.219.83",
      "service-proto": "tcp",
      "service-port": 80,
      "next-hop-ips": [
        "10.12.0.13",
        "10.12.0.141",
        "10.12.1.16"
      ],
      "next-hop-port": 80,
      "conntrack-enabled": true
    }
  ],
  "attributes": {
    "app": "nginx",
    "name": "nginx",
    "namespace": "default",
    "service-name": "default_nginx"
  }
`
```

Figure 33

Effectively, the Cisco ACI CNI plugin implements a distributed load balancer on Open vSwitch in order to implement ClusterIP services. This is transparent to the cluster's DNS service discovery. Traffic from any Pod accessing the service ClusterIP and/or service name is load balanced to the right Pods.

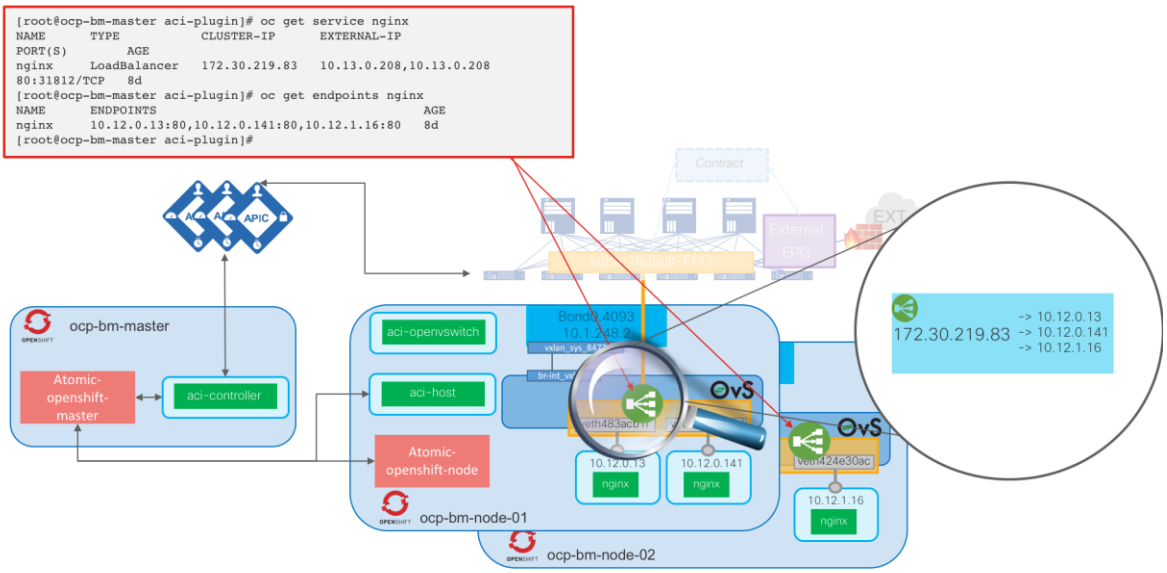

Figure 34: The APIC programs a distributed load balancer on OVS for ClusterIP

ClusterIP service IP addresses are automatically associated with DNS entries on the OpenShift cluster for service discovery purposes. The ACI CNI plugin is completely transparent in this sense and OpenShift DNS-based service discovery works perfectly fine.

5.4.4. Consolidated Visibility of Kubernetes Networking via APIC VMM

Integration

The VMM integration allows APIC to learn and model virtual endpoints as they connect to the fabric. This is based on a control and management plane integration between the APIC and the domain controller. When using the Cisco ACI CNI plugin, the VMM integration is implemented through the aci-containers-controller and the opflex agent running on each OpenShift node. Each OpenShift cluster running the Cisco ACI CNI plugin represents a Container Domain, compDom class in the APIC object model, of type OpenShift. Each node running an opflex agent represents an object of class opflexODev in the APIC model with details of the physical path connecting it and the status of the node. In Figure 34 we show a few combined screenshots that illustrate these concepts. The 'oc get nodes' helps an OpenShift administrator list the nodes part of the cluster. The fabric

administrator no longer has to see these nodes as just unknown servers connected to a fabric switch. Instead, APIC has the inventory of nodes of the cluster and it is now easy for the fabric administrator to immediately know the role of every server and where they are in the physical fabric.

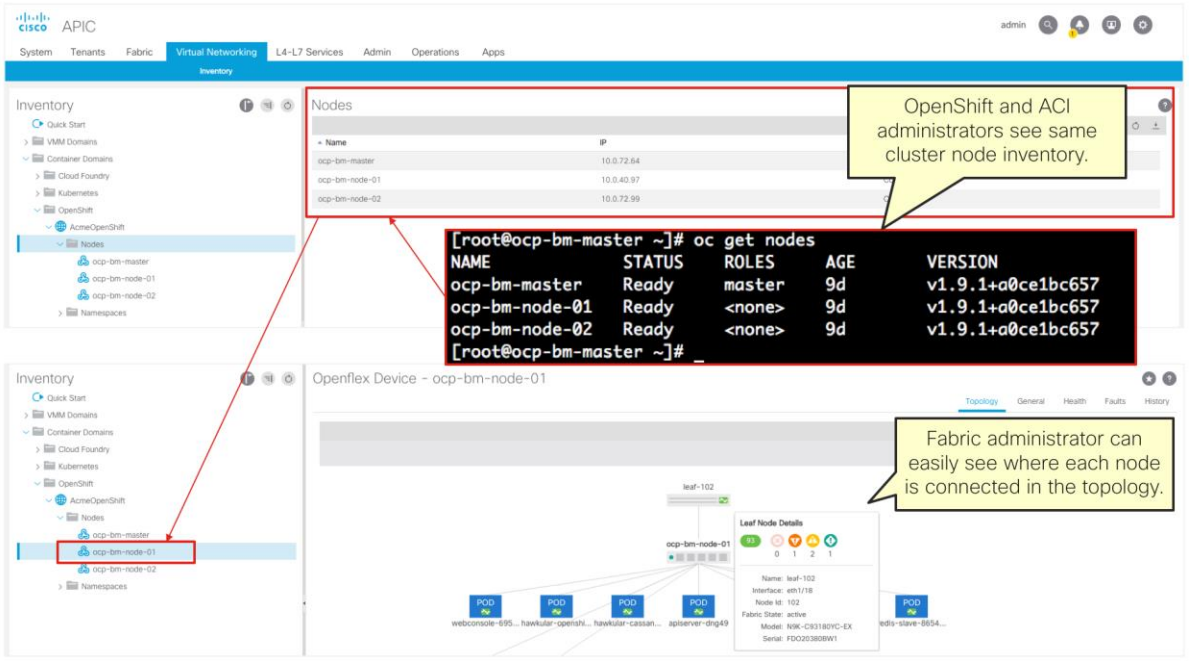

Figure 35: VMM integration provides fabric administrators with visibility

The VMM integration with OpenShift not only provides node-level visibility, but also visibility into the Kubernetes model and endpoints. Each OpenShift project is effectively a Kubernetes namespace which is mapped in the APIC object model to an object of class compNameSpace. The following table summarizes the elements of the OpenShift cluster modeled by the APIC VMM:

OpenShift object	APIC object class	Information
Project/Namespace	compNameSpace	List of all namespaces and Pods running on them
Deployment	compDeployment	List of deployments in a namespace, number of replicas and Pod details
ReplicaSet	compReplicaSet	List of all replicasets for corresponding deployments along with Pod details
Service	CompService	List of services with details of ports and protocols exposed and endpoints backing them.
Pod	compContGrp	shows EPG, IP, Mac encapsulation, physical path, stats
	opflexIDEp	List of Pods, tracking node allocation, physical and virtual network information, IP, MAC, statistics, etc.

Table 4

The main objective of the VMM integration is to facilitate operations. This is accomplished by giving context to the fabric administrator, so that a network endpoint is no longer just seen as a Mac address learnt on a switchport, physical or virtual, but instead can be immediately associated to its IP address, role, format and location.

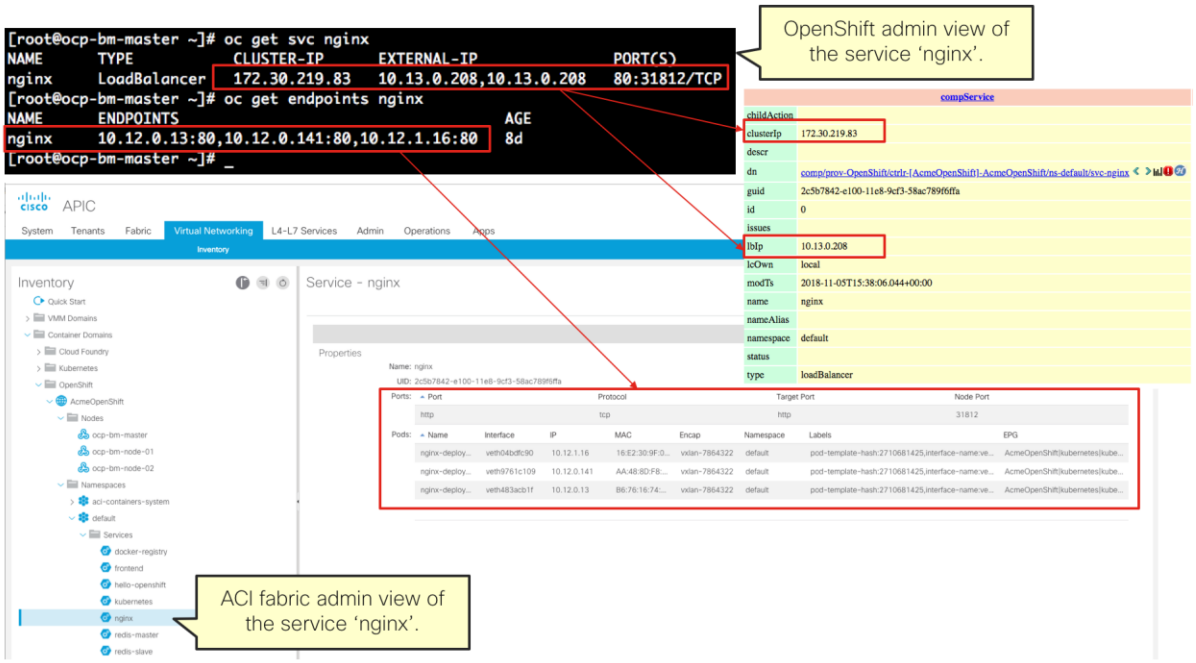

Figure 36: An OpenShift LoadBalancer service as seen in the VMM and object model

For instance, on Figure 35 we show a service object NGINX and associated endpoints as seen by the OpenShift administrator on the 'oc' CLI. The fabric administrator can see the same information using the APIC GUI and/or the Visore object browser, thus recognizing that an IP address is part of a service object, and therefore intends to load balance to other elements and immediately seeing those Pod elements along with its entire network path: virtual port on Open vSwitch, encapsulation, labels, and EPG. By looking at the Pod details the administrator can then see the node on which the Pod is running and correlate the physical path with the virtual automatically without requiring external tools that are both expensive and always outdated.

APIC can also gather statistics from the opflex agent. In Figure 36 we see a Pod, which is represented in APIC as both a corresponding Pod object and its associated fabric endpoint information, and the network traffic statistics collected by the opflex agent.

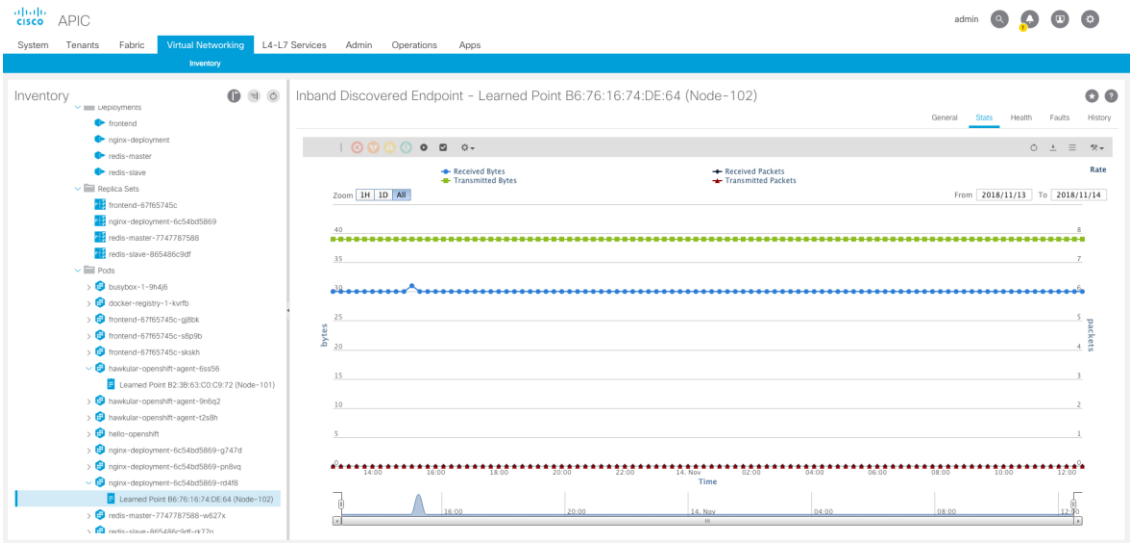

Figure 37: VMM statistics for an OpenShift Pod network traffic

This is of course not in detriment of the OpenShift administrator tracking metrics using their own tools, as seen in Figure 37 where we show the metrics seen on the OpenShift web console for the same nginx Pod. Each administrator can use the information on the tools they most commonly use.

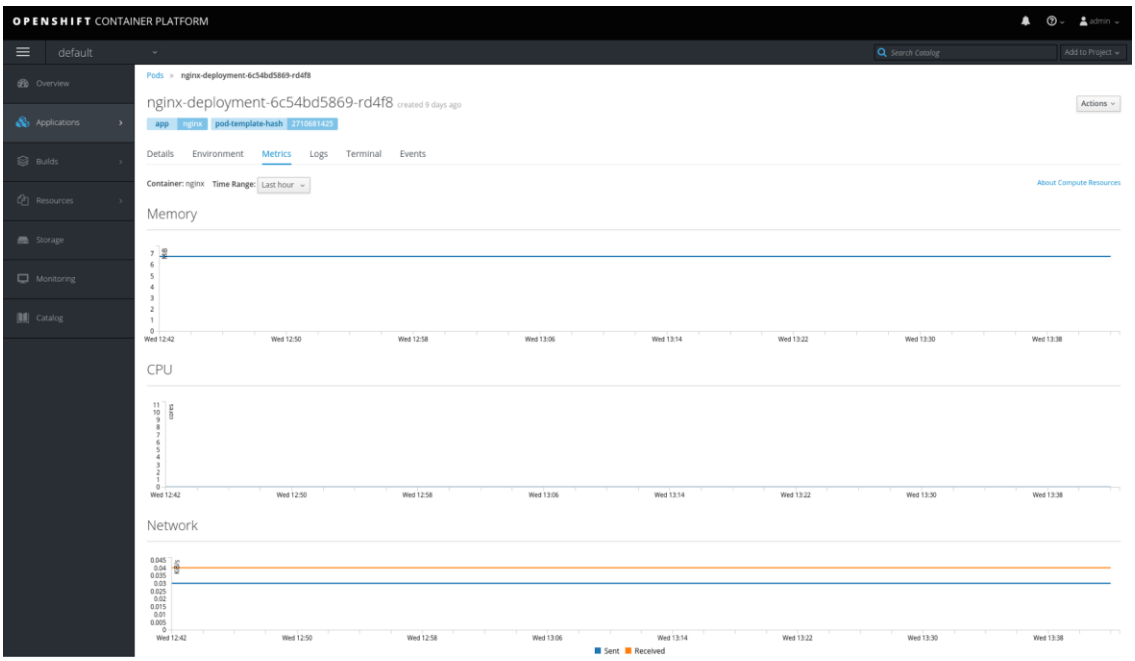

Figure 38: Web Console statistics for an OpenShift Pod network traffic

5.4.5. Distributed Hardware-Accelerated Load Balancer

When services provided by the cluster must be accessible to external endpoints, Kubernetes provides a different type of service object: the LoadBalancer service. This object calls a cloud controller that is plugin-specific and must create an external load balancer to reach the service. While the ClusterIP address associated to a service is internal to the cluster and only reachable by the cluster Pods, the LoadBalancer (External) IP address is accessible externally.

The Cisco ACI CNI plugin provides IP address management for LoadBalancer objects as well as a Layer4-level load balancer implemented on the fabric leaf switches using ACI Policy Based Redirect (PBR).

The Cisco ACI CNI plugin chooses IP addresses for external services from the configured `OpenShift_master_ingress_ip_network_cidr`[2] to provide them to service objects configured as type LoadBalancer. This CIDR is not configured on any Bridge Domain in the ACI fabric.

We can better explain this by following an example. For instance, below we reproduce again the output of the example NGINX service we have been showing before.

```
[root@ocp-bm-master aci-plugin]# oc get service nginx
NAME      TYPE           CLUSTER-IP      EXTERNAL-IP
PORT(S)        AGE
nginx     LoadBalancer   172.30.219.83   10.13.0.208,10.13.0.208
80:31812/TCP   8d
```

Figure 39

The cluster CIDR for external services is configured as 10.13.0.0/24. The Cisco ACI CNI plugin has chosen the IP address 10.13.0.208 as the EXTERNAL-IP for the nginx service. This IP address must be routable outside of the ACI fabric, but it is not a fabric endpoint. Since 10.13.0.208 does not correspond to a fabric endpoint, the IP address is known to the fabric via an externalEPG associated to the L3Out selected for the OpenShift cluster.

[2] The openshift_master_ingress_ip_network_cidr parameter should match the configured CIDR on the extern_dynamic parameter of the acc-provision configuration file.

For each service exposed as a LoadBalancer, the aci-containers-controller creates an external EPG that matches the service's external IP address. In fact, whenever a new service is exposed by the OpenShift user, the aci-containers-controller automatically performs several configurations on the APIC:

1. Create a new external EPG under the cluster's L3Out interface. The external EPG is named concatenating the cluster VMM name, the project name and the service name (i.e. AcmeOpenShift_svc_default_nginx). The subnet added corresponds to the external IP address with a prefix of 32 bits (i.e. 10.13.0.208/32).
2. Create a contract and associated filters to match on the specific protocols and ports exposed by the OpenShift service. The contract is created under the tenant where the L3Out is configured and its name is built concatenating the cluster VMM name, the project name and the service name (i.e. AcmeOpenShift_svc_default_nginx).
3. Create a PBR redirection policy for the service. Again this object is named concatenating the cluster VMM name, the project name and the service name (i.e. AcmeOpenShift_svc_default_nginx). The redirection policy redirects to any node that has active Pods in the endpoint object associated with the service.
4. Deploy a PBR Service Graph based on the Cluster's L4-7 Service Graph template using the PBR redirection policy from point (3) and associates the Service Graph with the contract from the point (2).
5. Configure the default external EPG to provide the contract created for the service in point (2), and the service's external EPG from point (1) to consume it.

It is outside the scope of this document to explain in detail how ACI PBR work. However, some understanding is important. PBR allows the ACI leaf switches to make a decision to redirect traffic from its normal routing or switching path depending on whether the traffic matches a given policy specified in terms of Layer 4 port and protocol as defined in an ACI contract. Once traffic matches, the ACI fabric needs to know how to reach the redirection point. This is specified in a redirection policy.

The redirection endpoint is defined with the IP and MAC address of the endpoint to redirect the traffic to. This endpoint must be known to the fabric. In the case of OpenShift or Kubernetes clusters, the redirection endpoints can be any OpenShift node that run Pods that are part of the service backend. Creation of PBR entries is automatic, you don't need to worry about obtaining the correct IP and MAC address.

The fabric must be able to identify each node and have a network logical and physical path to redirect traffic to. For this to happen, first, a **Service Bridge Domain** and associated

VLAN ID is created by the aci-containers-controller for each OpenShift cluster with the ACI CNI plugin. This is the **bd-kubernetes-service** Bridge Domain described in section 5.2 and the VLAN specified in the `service_vlan` parameter of the acc-provision configuration file.

Second, an Opflex Service IP address is assigned to each OpenShift node. This address is automatically configured by the ACI CNI plugin on every node, chosen from the `node_svc_subnet` CIDR on the acc-provision configuration file. The IP address assigned to each node can be seen by looking at the node annotations as opflex.cisco.com/service-endpoint.

In Figure 39 we see an example for a cluster named AcmeOpenShift, using a shared L3Out named OSPF-LEAF-103-CSR1KV.

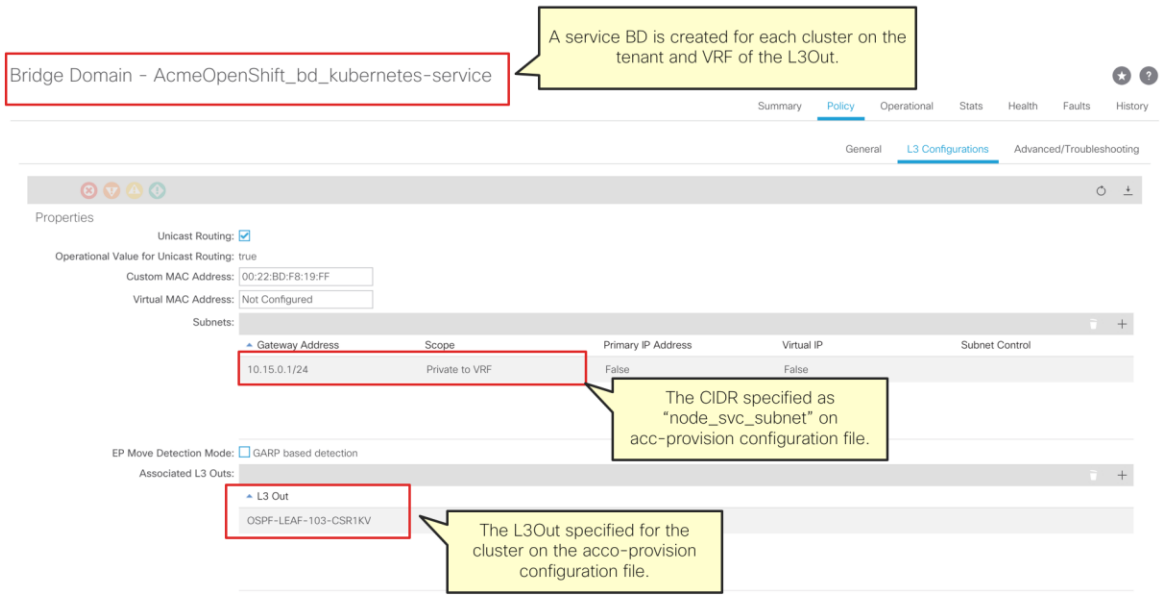

Figure 40: Service BD configuration example

It is important to understand that the `node_svc_subnet` CIDR (10.15.0.1/24 in the example if Figure 39) is private to the VRF and for practical purposes completely inaccessible by any endpoint connected on the VRF. These IP addresses are exclusively internal to the functioning of the PBR Load Balancing feature provided to the cluster.

Similarly, the `service_vlan` VLAN ID does not need to be configured in any OpenShift node or fabric leaf by the respective administrators. The aci-containers-controller enables this VLAN on the OpenShift node's Open vSwitch and on the upstream connected Leaf switches. In Figure 40 we show an OpenShift node ocp-bm-node-01 connected to

leaf-102 and the deployed EPGs on the corresponding leaf port: the default EPG for infraVLAN, kube-nodes, kube-default and a special EPG part of the fabric internal universe that is used to enable the service VLAN on the port.

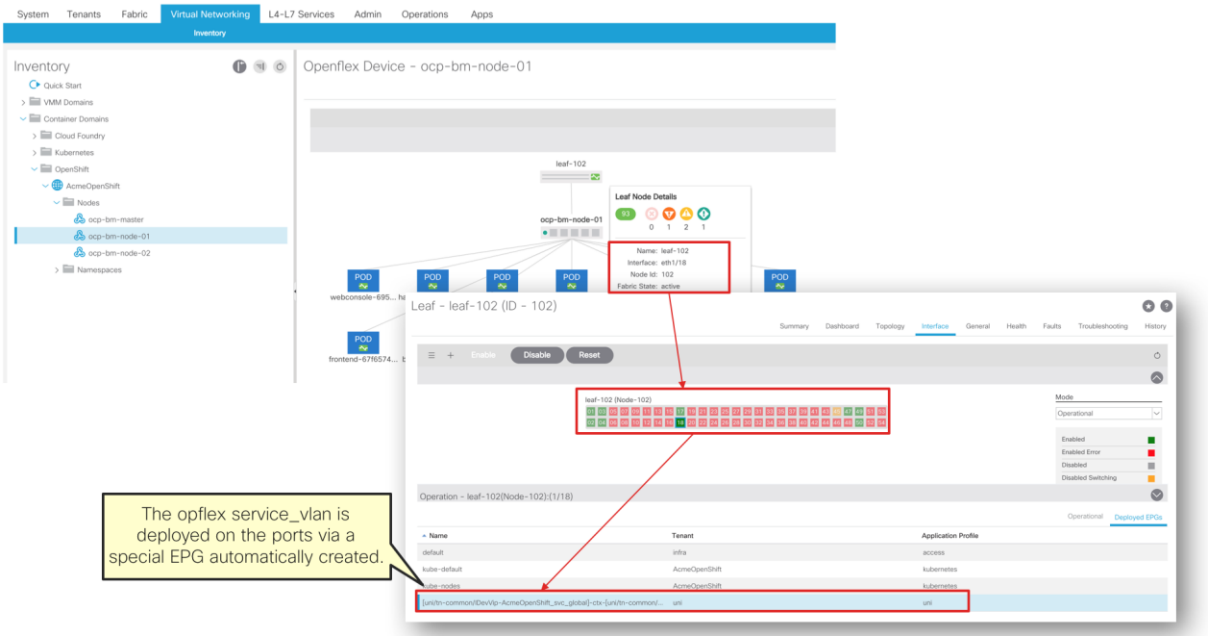

Figure 41: The service BD and corresponding VLAN is enabled on all ports that require it

In case the OpenShift node runs nested in a connected hypervisor, this VLAN must be trunked to the node's vNIC.

To illustrate how PBR works to implement LoadBalancer services we will look at an example in detail. In Figure 41 we see a representation of an OpenShift cluster connected to the ACI fabric running the ACI CNI plugin where components such as ACI containers, OpenShift master, etc. have been eliminated for simplicity. The graphic illustrates the cluster associated L3Out interface configured on a pair of border leaf switches. The connected router must have a route for the `OpenShift_master_ingress_ip_network_cidr`, in the example 10.13.0.0/16, pointing to the L3Out interface as next hop.

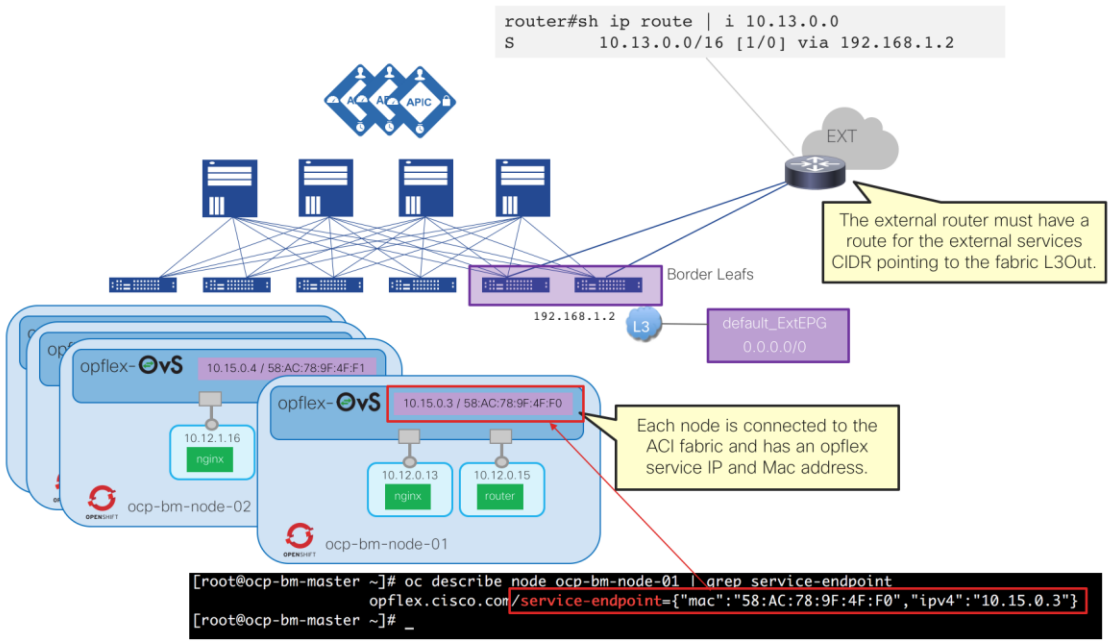

Figure 42: The service-endpoint IP address used for PBR

The L3Out interface has associated an external EPG that acts as the default for the OpenShift cluster and is matching on 0.0.0.0/0, therefore matching on all incoming traffic. The figure also illustrates the annotation of the ocp-bm-node-01 OpenShift node with the opflex service endpoint IP, 10.15.0.3. This IP address is not configured on any interface on the OpenShift node. Instead, the opflex-controller Open vSwitch has entries to allow the agent to respond to ARP and ICMP probes from the fabric for this IP address, so it is known as a fabric endpoint as we can see below on the APIC EP tracker and/or APIC CLI.

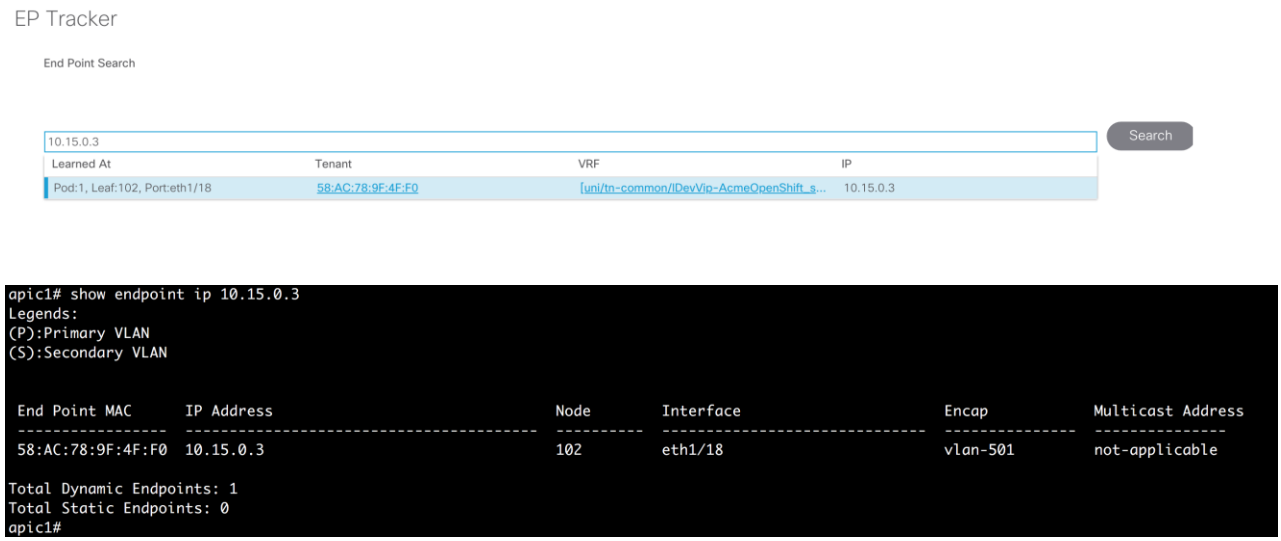

Figure 43: The service-endpoint IP address as seen in the fabric

The fabric knows the opflex service endpoint IP/MAC for every OpenShift node in the cluster, learnt on the service bridge domain.

Now let's imagine that a service is exposed to reach an NGINX web server backed with a Deployment with three replicas. The following image shows the service as seen on the OpenShift Web Console, with an external IP of 10.13.0.208 exposing port tcp/80.

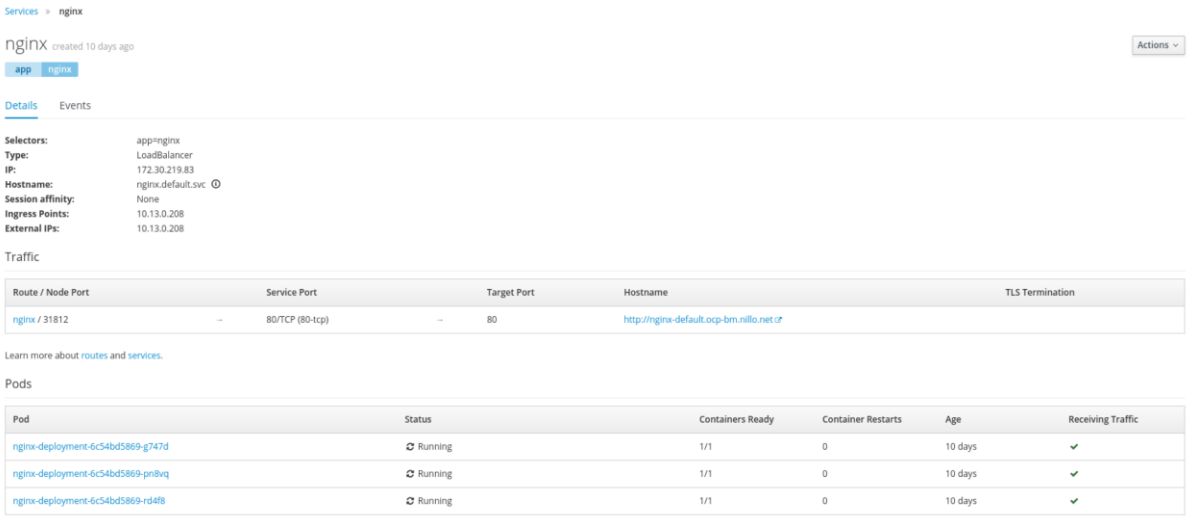

Figure 44: An NGINX service exposed as LoadBalancer as seen on WebConsole

When the service is created with type LoadBalancer, the aci-containers-controller creates the required objects in the APIC as illustrated on Figure 44.

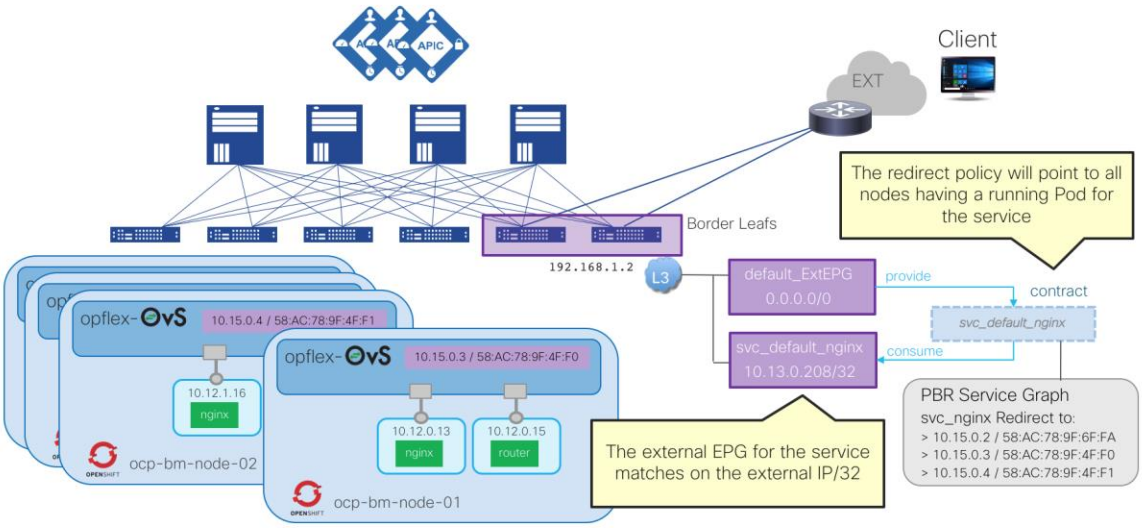

Figure 45: The PBR service graph to implement an external IP

This includes an external EPG matching on the external IP of the service (10.13.0.208 in the example), a contract between the default external EPG and the service external EPG and a PBR Service Graph with a dedicated redirection policy for the service. In Figure 45 we see the PBR redirection policy in ACI for the NGINX service. The image shows one of the NGINX Pods running on ocp-bm-node-01 and the opflex service IP of the node, 10.15.0.3. Because the NGINX service is backed by multiple Pods running on diferent nodes, we see the redirection policy includes a list of opflex service IPs: 10.15.0.2, 10.15.0.3, 10.15.0.4.

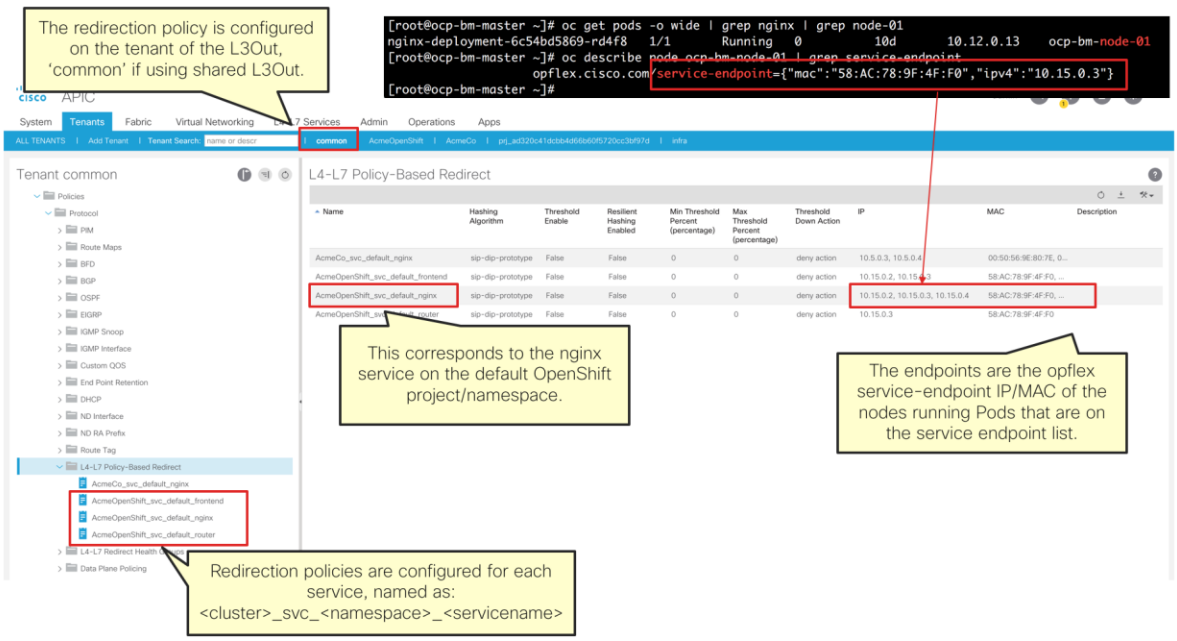

Figure 46: The PBR redirection policy for an external IP service

The aci-containers-controller monitors the kubernetes endpoint API to learn if there are Pods that are added or removed to back the service object. If Pods are added on new OpenShift nodes, the PBR redirection policy is updated to include those nodes' service IP address.

Now let's look at the packet flow when an external client accesses the external service IP address, 10.13.0.208. We assume the external router has a route for the extern_static subnet3. The client sources the packet with 192.168.2.2 and sends it to its default gateway that eventually routes it towards the L3Out.

[3] This route can be dynamically advertised, see https://www.cisco.com/c/en/us/td/docs/switches/datacenter/aci/apic/sw/kb/b_Cisco_ACI_and_OpenShift_Integration.html#id_90196

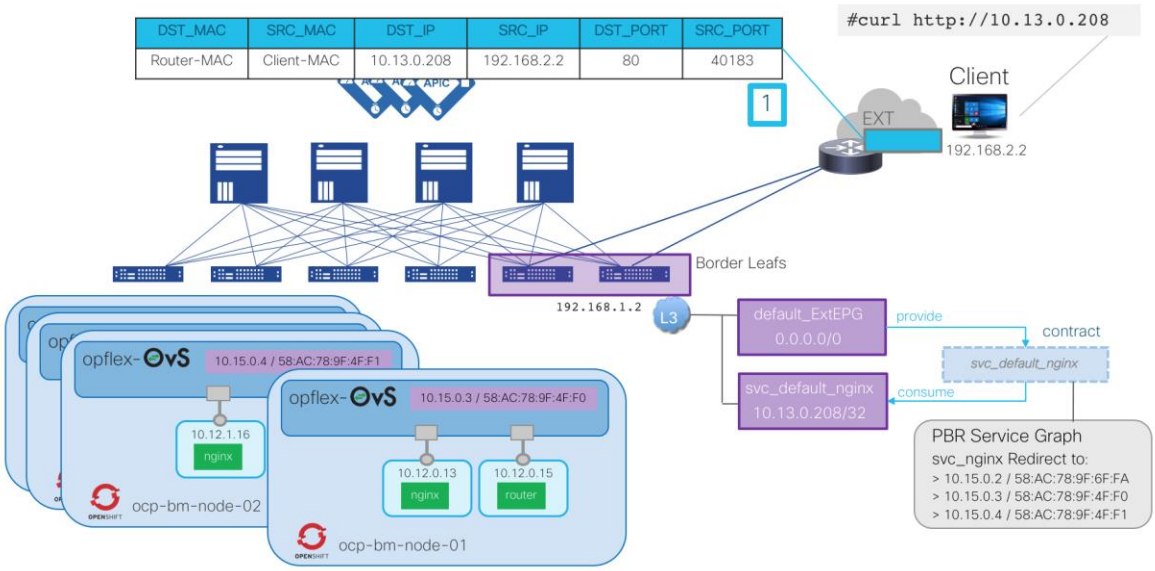

Figure 47: Packet walk of accessing an external IP via PBR Service Graph

As the packet reaches the L3Out on the border leaf, the source IP matches the default external EPG classification, but the destination 10.13.0.208/32 matches the NGINX service external EPG, and contract between the two applies.

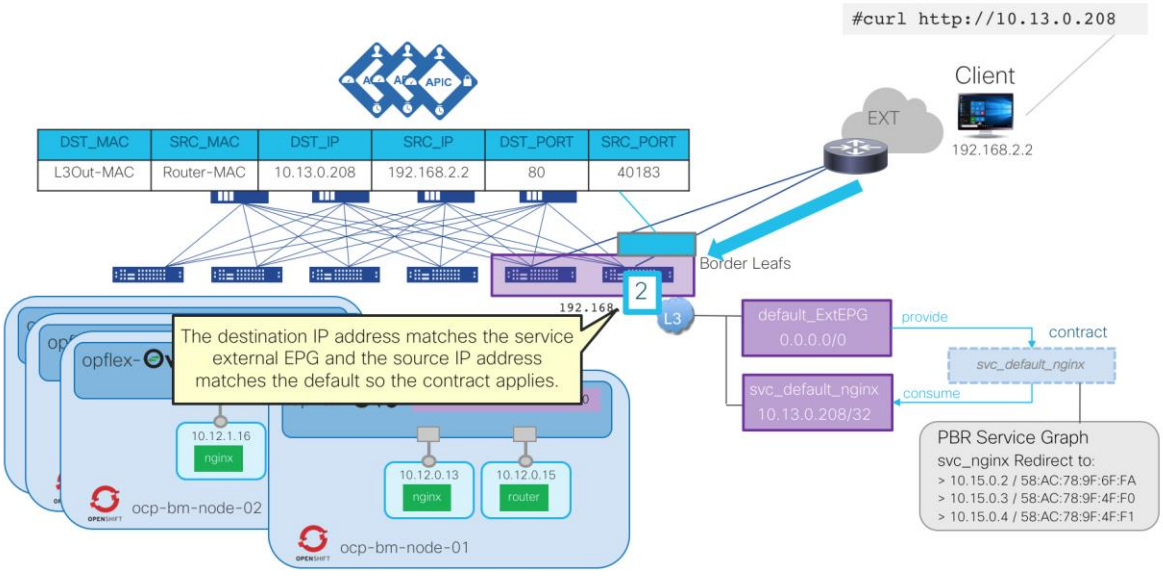

Figure 48: Packet walk of accessing an external IP via PBR Service Graph

This contract has a PBR Service Graph attached which has three redirection endpoints corresponding to the nodes with NGINX pods running. The 5-tuple of the packet is hashed

to select one of the nodes. Subsequent packets of the same flow is redirected always to the same node for the duration of the flow. The redirection policy helps finding out the next-hop MAC address and the packet is sent over the service Bridge Domain to the egress VTEP leaf connected to the OpenShift node.

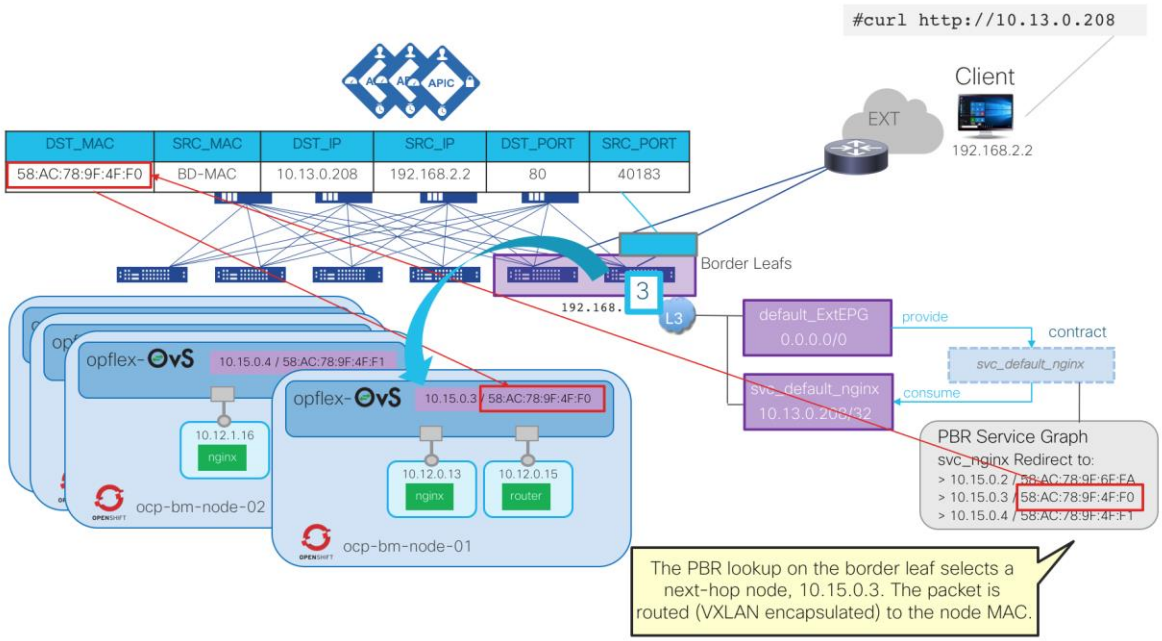

Figure 49: Packet walk of accessing an external IP via PBR Service Graph

The packet reaches the Open vSwitch of the OpenShift node, where opflex has configured entries to accept traffic to the opflex service MAC address and to NAT the external service IP, 10.13.0.208 in the example, to the Pod's IP address, 10.12.0.13. If more than one Pod was running on the node for the given service, a second stage load balancing decision would take place obviously.

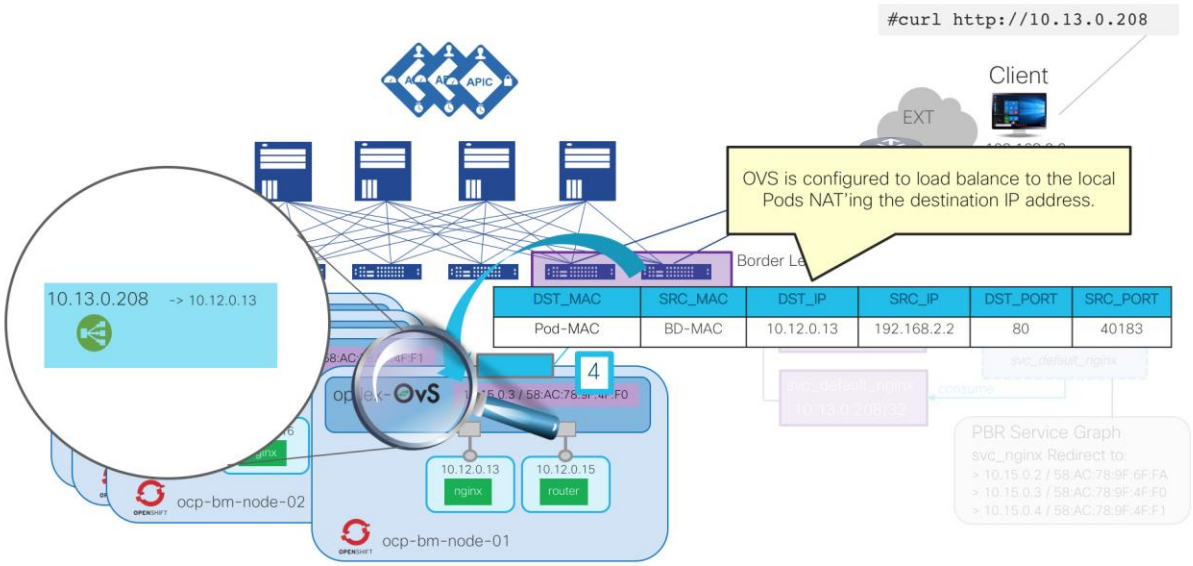

Figure 50: Packet walk of accessing an external IP via PBR Service Graph

The packet is delivered to the Pod's IP address, sourced from the client's IP address. The NGINX server can prepare its response.

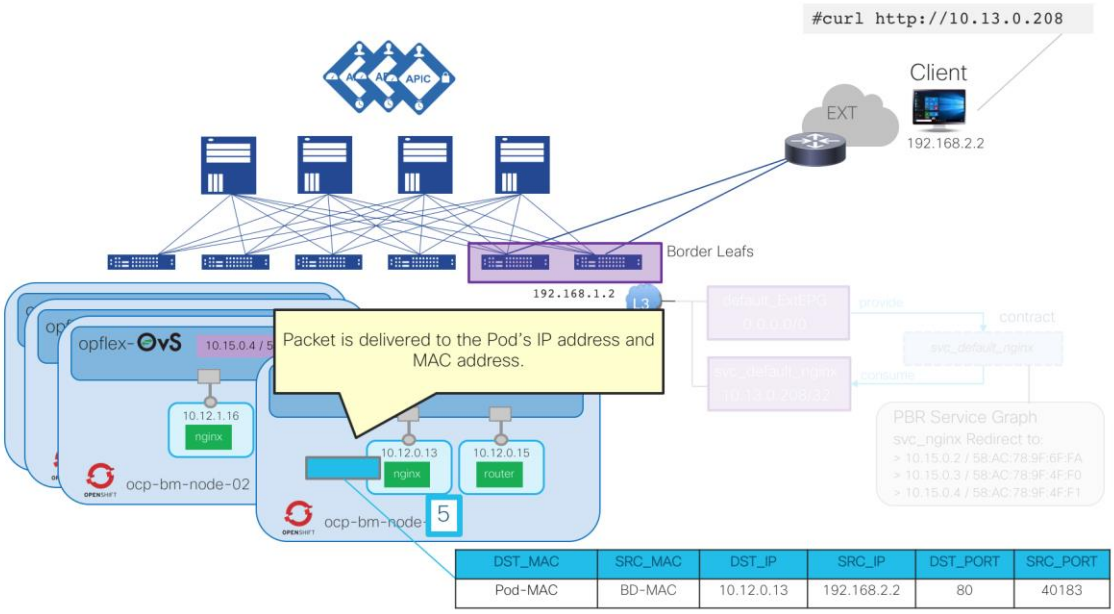

Figure 51: Packet walk of accessing an external IP via PBR Service Graph

The reply packets are sent to an IP address that is not local, therefore the NGINX Pod sends to its default gateway's MAC address: the kube-pod-bd MAC address.

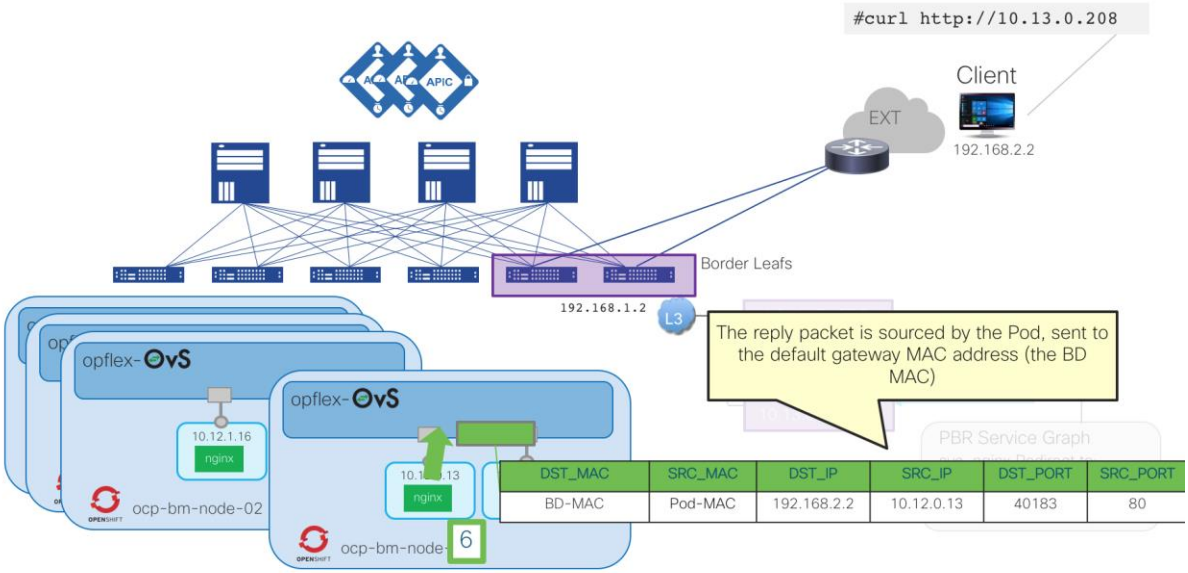

Figure 52: Packet walk of accessing an external IP via PBR Service Graph

The packet is intercepted by rules programmed at Open vSwitch that identify the packet as being part of an existing connection. These rules do source NAT to replace the Pod's IP address – 10.12.0.13 – with the external Service IP of 10.13.0.208. The packet is then sent to the leaf over the service Bridge Domain to be routed in the fabric.

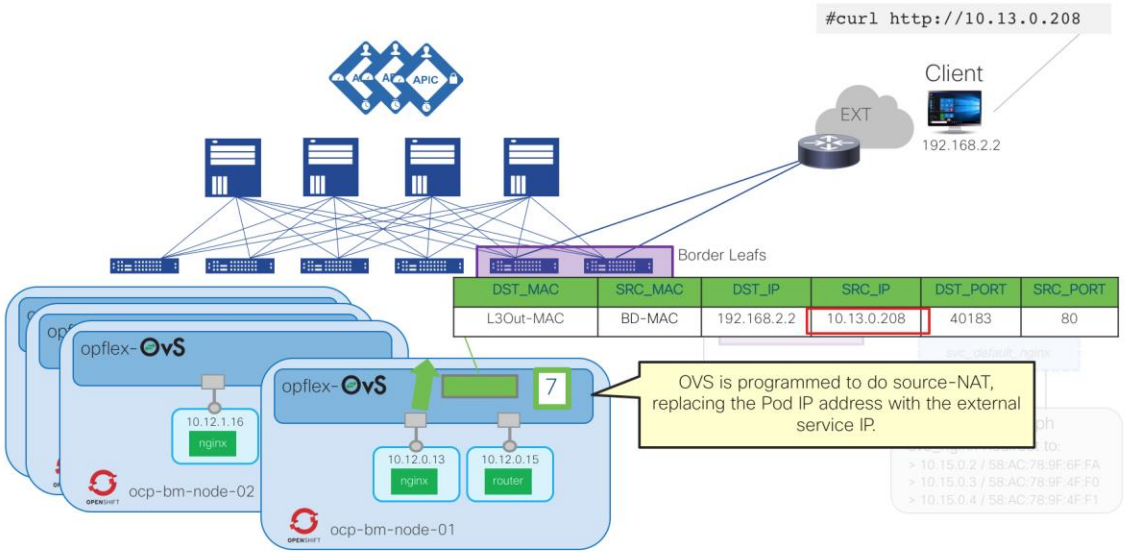

Figure 53: Packet walk of accessing an external IP via PBR Service Graph

At the first hop leaf, the packet is coming from an internal special EPG, and therefore it

does not match the PBR redirection which is only between the two external EPGs of the L3Out. The destination IP address however matches the default external EPG and the packet is routed to the border leaf.

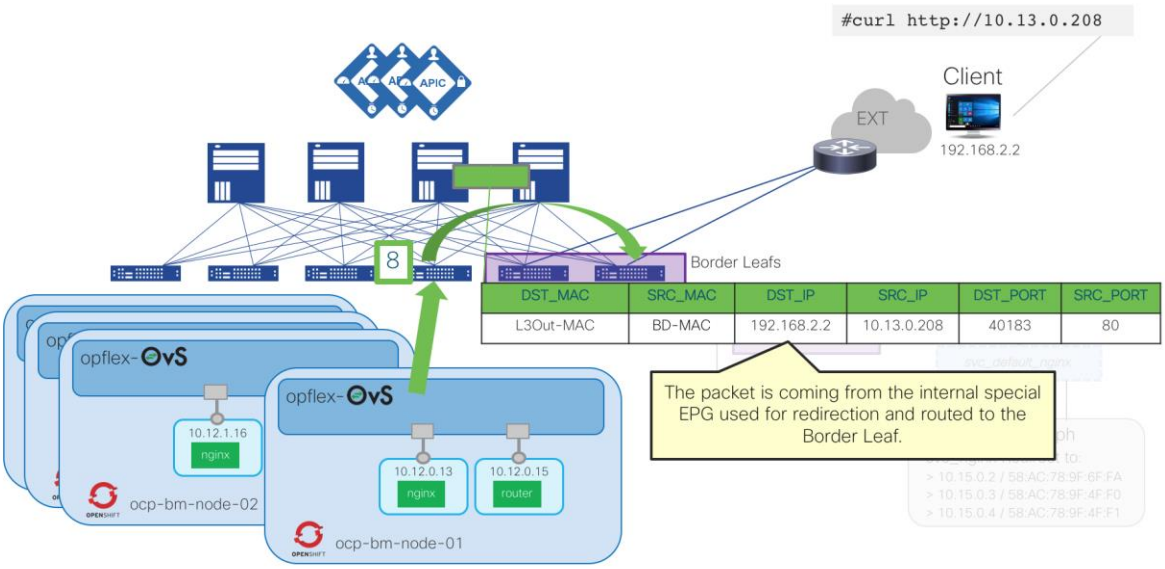

Figure 54: Packet walk of accessing an external IP via PBR Service Graph

Finally, the packet is routed at the Border Leaf towards the external router and eventually to the originating client. The client receives the packet sources from the external service IP, and not from the Pod IP.

5.4.6. Distributed Firewall for Network Policies

OpenShift can leverage Kubernetes NetworkPolicy objects to define a micro segmentation security model for applications. This capability was introduced to OpenShift 3.5 as Tech Preview and was made Generally Available (GA) in 3.7 with supported CNI plugins.

NetworkPolicy objects define a white-list security model. In other words: all traffic is denied except traffic explicitly allowed by the policy. Policies are applied to Pods by matching on a number of selector fields. The selector can match on items such has namespace and Pod labels. These policies can be owned by developers, OpenShift administrators, network or security administrators. Given the declarative nature of NetworkPolicies, they can be added to the OpenShift applications as part of their lifecycle.

The Cisco ACI CNI plugin supports NetworkPolicy objects. Cisco ACI's native policy model revolves around establishing contracts that define the connectivity allowed between groups of endpoints (EPGs). However, native NetworkPolicy is not made of contracts between EPGs. Therefore, it is represented using another policy object in APIC called Host Protection Profiles (HPP; `hostprot:Pol` object class in APIC object model).

Host Protection Profiles enable APIC to represent security models such as Neutron Security Groups and Kubernetes NetworkPolicies. The HPP is implemented with a tenant-level object called `hostprot:Pol` and enables composable policies to be applied to a Virtual Machine or container virtual Ethernet interface by forming relationships with their corresponding `opflex:IDEp` endpoint objects.

HPP are communicated to the Opflex Agent on the OpenShift nodes where there are Pods that require them to implement NetworkPolicy. The Opflex Agent in turn creates Openflow rules on Open vSwitch to implement stateful firewall rules that enforce the required configuration.

```
kind: NetworkPolicy
apiVersion: networking.k8s.io/v1
metadata:
  name: allow-redis-frontend
spec:
  policyTypes:
  - Ingress
  podSelector:
    matchLabels:
      app: redis
      tier: backend
  ingress:
  - from:
    - podSelector:
        matchLabels:
          app: guestbook
          tier: frontend
    ports:
    - protocol: TCP
      port: 6379
```

Figure 55

To illustrate how this works we will look at a basic example above these lines where we can see a network policy named 'allow-redis-frontend'. This network policy applies ingress filters to Pods that match the labels "app: redis" and "tier: backend". The filters are configured to allow traffic to the selected Pods from others matching the labels "app: guestbook" and "tier: frontend", only permitting connectivity to tcp/6379.

That network policy is translated by APIC into a tenant-level Host Protection Policy profile

like so (we are showing JSON notation just for better readability):

```
{
 "hostprotRule": {
      "attributes": {
           "annotation": "",
           "childAction": "",
           "connTrack": "reflexive",
           "descr": "",
           "direction": "ingress",
           "dn": "uni/tn-AcmeOpenShift/pol-
AcmeOpenShift_np_default_allow-redis-frontend/subj-networkpolicy-
ingress/rule-0_0",
           "ethertype": "ipv4",
           "extMngdBy": "",
           "fromPort": "unspecified",
           "icmpCode": "0",
           "icmpType": "0",
           "monPolDn": "uni/tn-common/monepg-default",
           "name": "0_0",
           "protocol": "tcp",
           "status": "",
           "toPort": "6379",
           "uid": "13451"
       }
 }
```

Figure 56

The Host Protection policies created to implement OpenShift NetworkPolicy objects can also be seen on the APIC GUI, as shown in Figure 56. We see the YAML text description of the network policy and the object created on APIC that corresponds to the JSON object shown above.

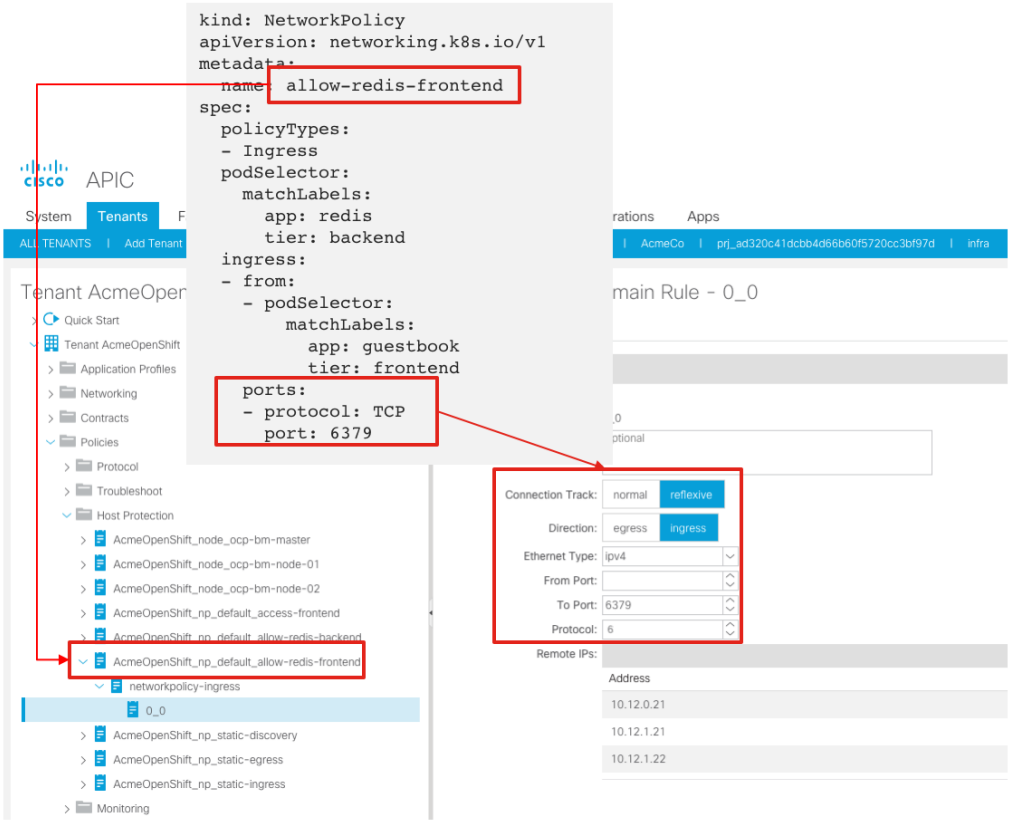

Figure 57: A NetworkPolicy object and corresponding Host Protection Policy

On Figure 57 we can also see a list of IP addresses that in this example correspond to frontend Pods that are allowed to communicate with the 'redis' backend as per the configured NetworkPolicy.

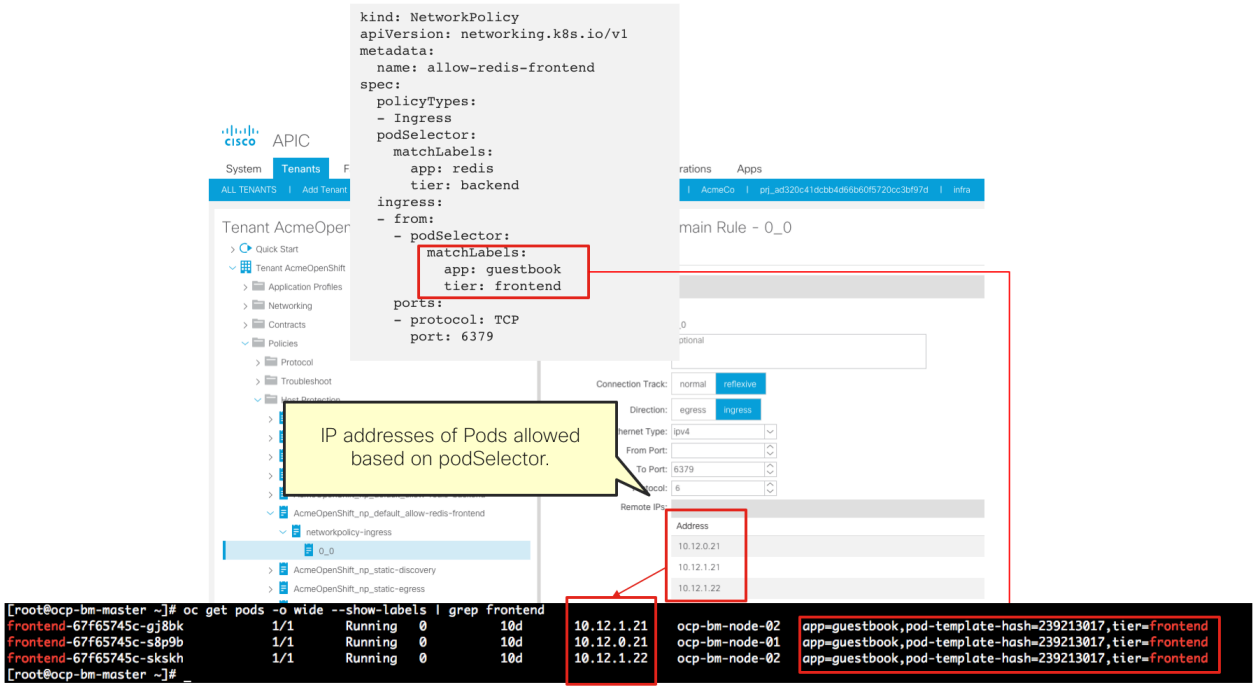

Figure 58: A NetworkPolicy object and corresponding Host Protection Policy

Effectively this means that you can have many Pods on the same EPG, for instance on the kube-default EPG, and microsegment all traffic between them using a stateful firewall programmed on Open vSwitch by the opflex agent.

We can see this illustrated in Figure 58 where multiple frontend Pods, a redis Pod and a busybox Pod running on two different nodes and all connected to the same kube-default EPG. We illustrate the firewall rules that are programmed by the opflex agent as required to implement NetworkPolicy.

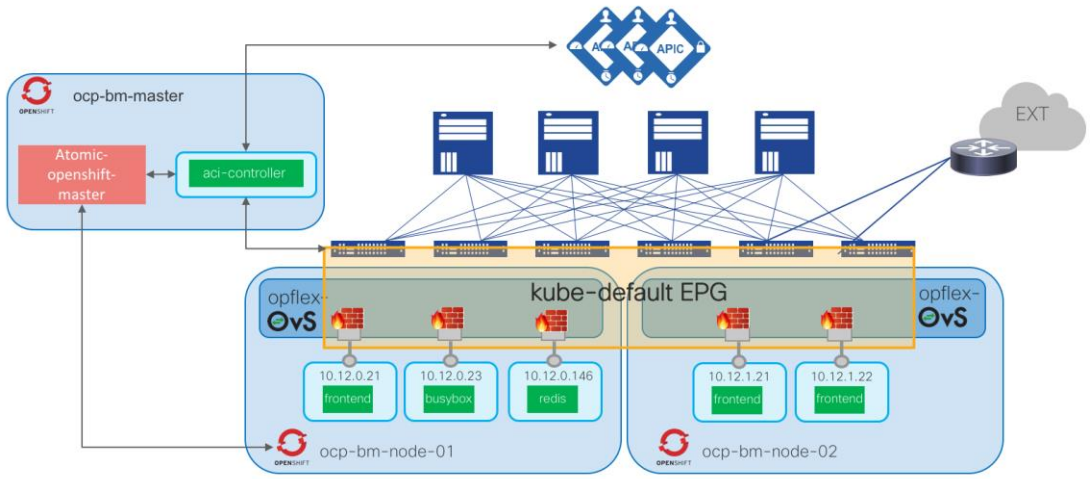

Figure 59: Using NetworkPolicy objects to implement a distributed firewall for Pods

We have already seen the NetworkPolicy allow-redis-frontend described earlier and how it is seen in APIC (see Figure 56). In Figure 59 we can see a view of the OpenFlow rules programmed for the selected Pod redis (redis-master specifically).

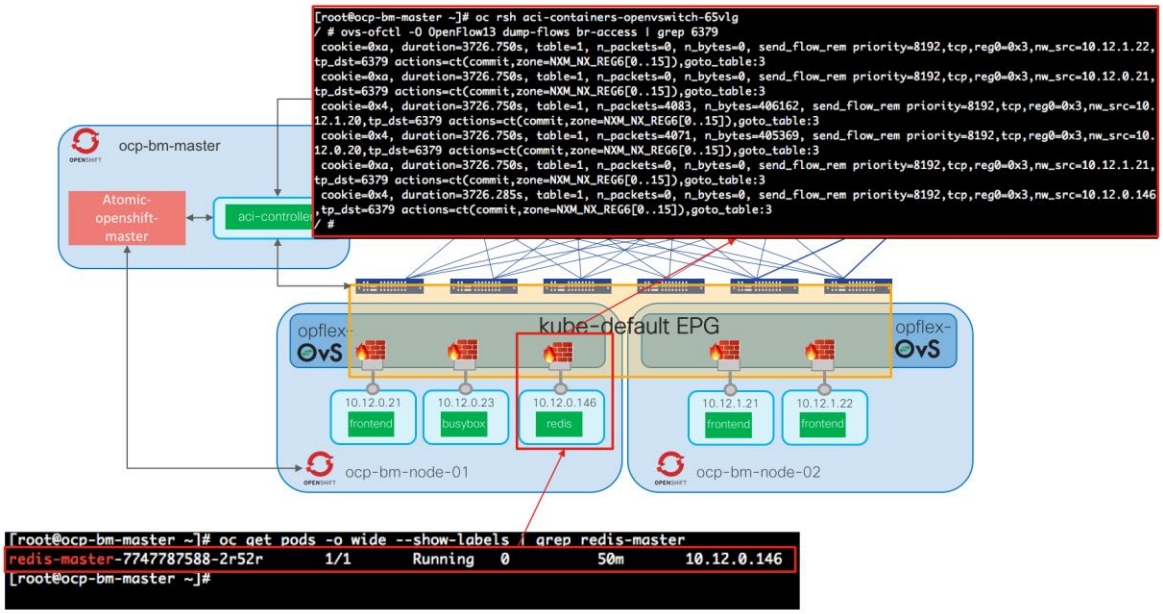

Figure 60: Host Protection Policy implemented as OVS OpenFlow rules

Those rules allow TCP/6379 only to the redis-master and only from the frontend Pod IP addresses. This means that despite being on the same EPG and on the same node, traffic

from the local frontend Pod is allowed only to tcp/6379 and no traffic at all is allowed from the busybox Pod since it does not match any policy, as we illustrate on Figure 60.

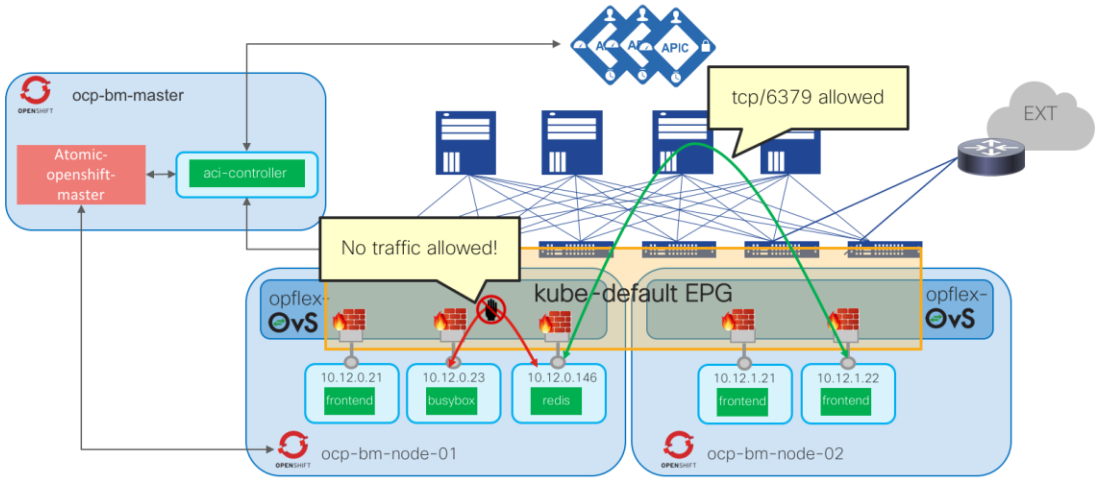

Figure 61: Host Protection Policy are enforced locally and between nodes

The OpenShift administrator, security administrator, etc. can apply the NetworkPolicy by applying the YAML file described earlier directly on the CLI or by using the Web Console as seen below.

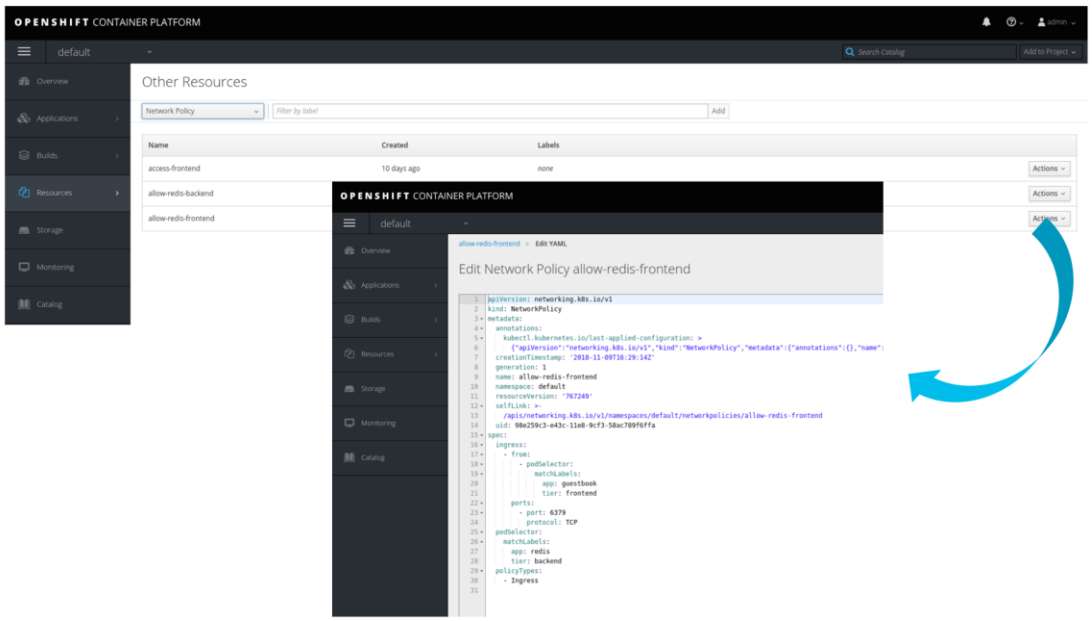

Figure 62: NetworkPolicy objects as seen on the Web Console

Also, from the web console it is possible to see for every Pod which policies are applied by

looking at the Pod annotations, where we see all required policies implemented by the Cisco ACI CNI plugin. We show the same example for the redis-master Pod in Figure 62.

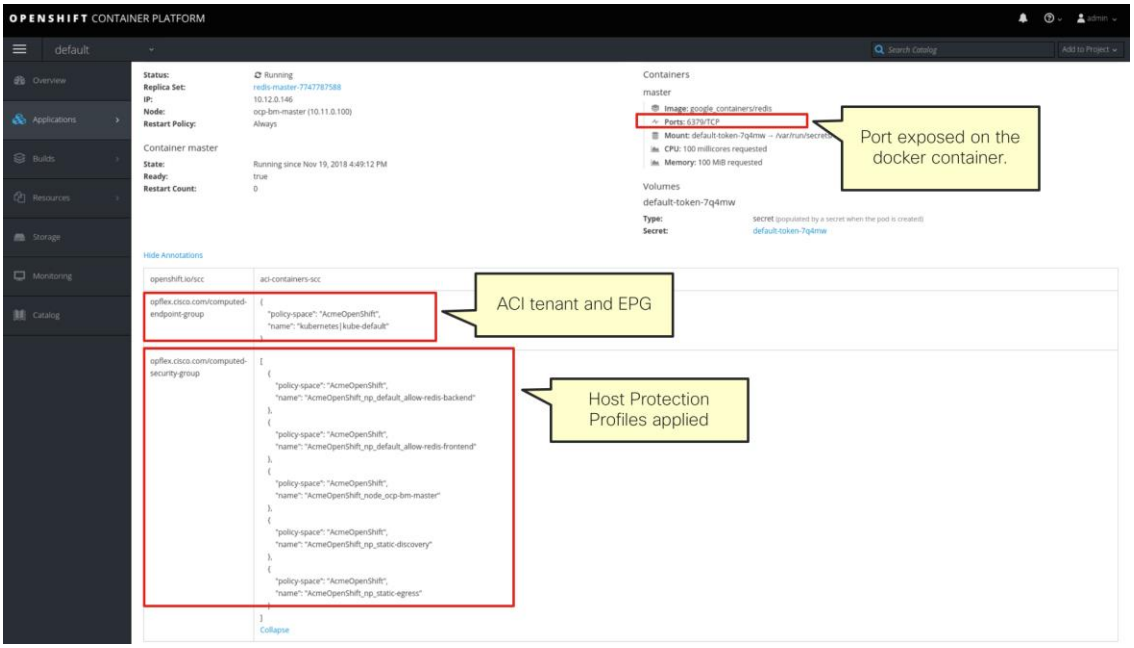

Figure 63: Pod details showing ACI annotations

Once again, the goal of the ACI CNI plugin is to provide network and security capabilities as well as facilitate operations. Both OpenShift and APIC operators can see the configured network policies.

NetworkPolicy can be used to provide segmentation at various levels. You can use it to isolate different namespaces, or tiers of an application. It is outside of the scope of this document to describe how to best use NetworkPolicy objects, however one important consideration is that if you define NetworkPolicy to isolate namespaces, you must always remember to allow connectivity back to the default namespace in order for applications to be exposed via the OpenShift routers. EPG-based segmentation might prove to be a simpler option if you're not intimately familiar with NetworkPolicy objects.

5.4.7. EPG-level Segmentation for Kubernetes Objects Using Annotations

The previous section explained how the Cisco ACI CNI plugin implements OpenShift Network Policies, which is the native way to implement micro segmentation in Kubernetes.

ACI has other ways to achieve segmentation; those are not limited to Kubernetes clusters. So far, we have seen the default and basic application profile created by the `acc-provisioning` tool to deploy connectivity OpenShift clusters and the Pods running on them. In that case, all OpenShift Pods from all namespaces are placed inside the kube-default EPG where any to any communication is permitted by default. Using NetworkPolicy on OpenShift, we saw how it is possible to restrict connectivity between namespaces and/or more granularly between application tiers, as seen in the previous section. This means NetworkPolicy can implement intra-EPG segmentation very easily.

It is also possible to connect Pods or entire namespaces to different EPGs. We have already seen a hint of this in Figure 62, where you can see the annotations for a Pod as seen on the OpenShift Web Console, including the information about the tenant and EPG. You can use Kubernetes annotations to attach arbitrary metadata to objects. The metadata in an annotation can be small or large, structure or unstructured and does not have the character set restrictions imposed of Kubernetes labels.

The Cisco ACI CNI plugin leverages Kubernetes 'annotations' to indicate the EPG that a Pod must be connected to. The annotation syntax used is as follows:

```
opflex.cisco.com/endpoint-group='{"tenant":"NAME","app-profile":"APP-NAME","name":"EPG-NAME"}'
```

Figure 64

Essentially, you use the 'opflex.cisco.com/endpoint-group' annotation followed by a JSON object that specifies the tenant, application profile and EPG names. You can annotate an object at runtime by using the OpenShift Web Console or the 'oc annotate' CLI, or you can add the annotation to the YAML definition of the object at creation time.

You can use the opflex endpoint-group annotation on three types of objects:

- Namespace: by annotating a namespace, all pods created on that namespace/project are placed on a given EPG.
- DeploymentConfig: by annotating an OpenShift DeploymentConfig object, all pods created by the replicaSet of the DeploymentConfig are placed on the given EPG. Deployment-level annotations are more specific than namespace-level and win in case a pod has both level annotations. In OpenShift, DeploymentConfig can currently only be annotated at creation time through the use of a template. Annotating a DeploymentConfig after it is created has no effect. The following is an example of a valid annotation for a DeploymentConfig:

```
      kind: "DeploymentConfig"
      apiVersion: "v1"
      metadata:
        name: "frontend"
      spec:
        template:
          metadata:
            labels:
              name: "frontend"
            annotations:
              opflex.cisco.com/endpoint-group:
'{"tenant":"T1","app-profile":"APP","name":"EPG1"}'
          spec:
            containers:
              - name: "helloworld"
                image: "gcr.io/google-samples/gb-frontend:v4"
                ports:
                  - containerPort: 8080
                    protocol: "TCP"
      replicas: 1
      selector:
  -     name: "frontend"
```

- Pod: by annotating a Pod, it is placed on the given EPG. This is the most specific annotation and wins over a deployment or namespace level annotation.

Whatever the object annotated, it is important to understand the following points with respect to the selected EPG:

- The Tenant, Application Profile and EPG must exist prior to using annotations that results in Pods connecting to it. Otherwise, an error is logged by the aci-containers-controller as it tried to connect Pods to an inexistent EPG. It is therefore recommended to automate the creation of the EPG and contracts before launching Pods and Services. A simple Ansible playbook can be used for that purpose (see Annex A).
- The EPG must be associated to the Bridge Domain used for Pods, that is the kube-pod-bd created by the `acc-provision` tool. If this BD is created on a given tenant, then the Application Profile and EPGs used must be on the same tenant.
- The EPG must be associated with the OpenShift VMM Domain.
- The EPG must provide and consume the basic contracts used by the kube-default EPG on the Kubernetes application profile. At the very minimum, health-check, icmp, dns and kube-api should be added to the EPG.
- You should add a contract between the new EPG and the kube-default EPG to allow the Pods to reach the OpenShift routers (again, this is best achieved through automation)
- Note: you can use the ACI contract inheritance feature to reduce the configuration complexity here

As with other sections, we will look at an example to better illustrate how to use annotations. In Figure 64 we see how we can create a new Application Profile and a new EPG named NewEPG which is mapped to the VMM domain of the OpenShift cluster and the kube-pod-bd.

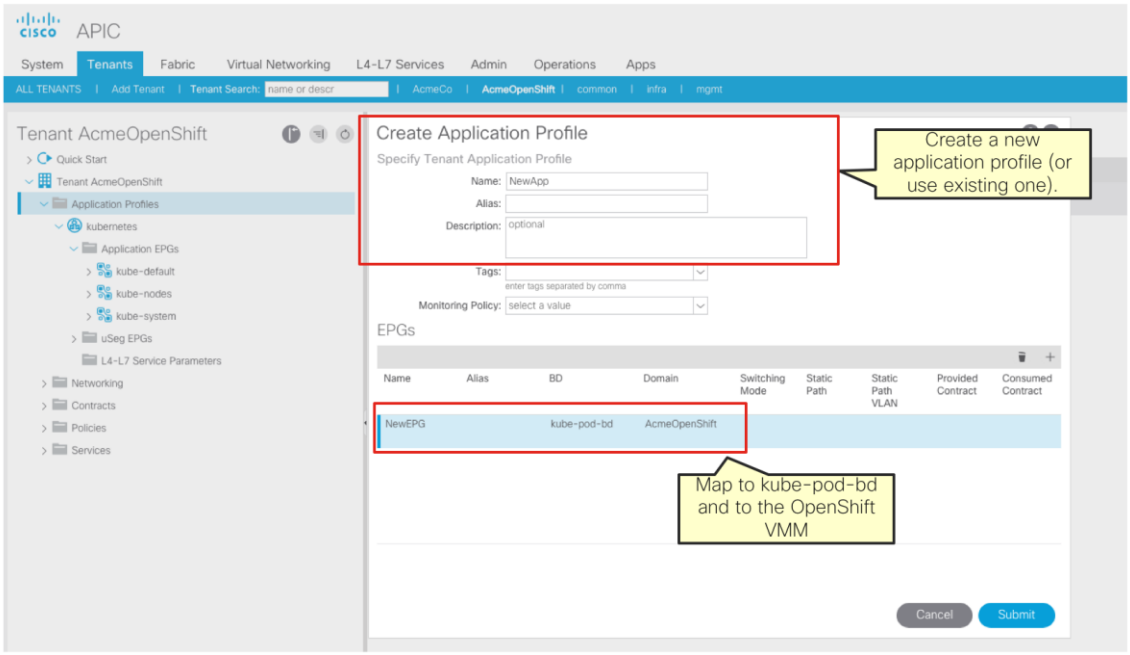

Figure 65: Creating a new EPG for OpenShift applications

To make sure NewEPG has all required contracts for OpenShift to function, we configure contract inheritance from kube-default by setting it as the master EPG, as seen in Figure 65.

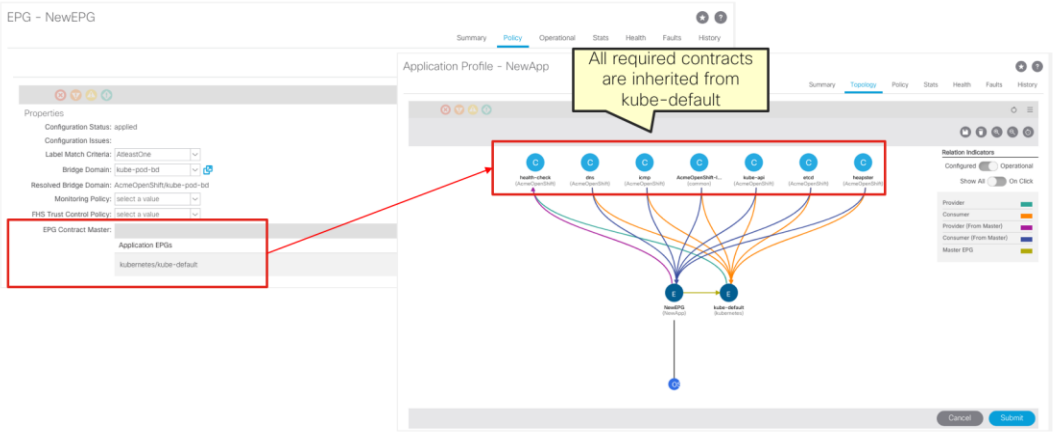

Figure 66: Creating a new EPG for OpenShift applications

Once this is done, in Figure 65 we show how the Pod can be annotated and is then reclassified onto NewEPG. Once this is done, the busybox Pod annotated can no longer reach the redis Pod on the same host even if all NetworkPolicy is removed. If communication is required, a contract can be added to enable the port and protocol of

choice. That contract is installed and enforced on the ACI leaf and on Open vSwitch, by means of the opflex agent.

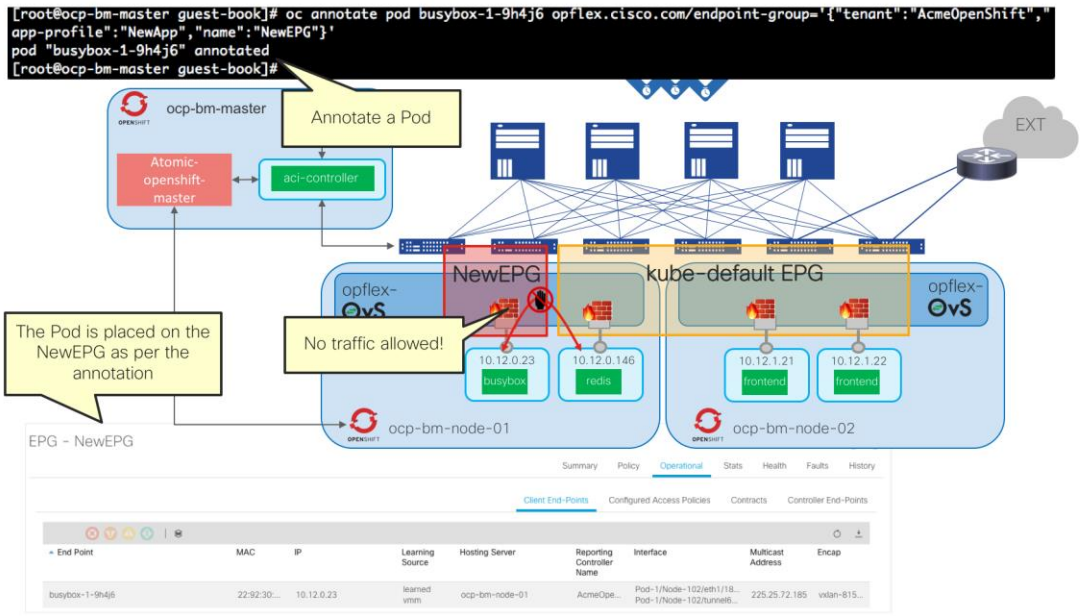

Figure 67: Using annotations to place a Pod on an EPG

5.4.8. Opflex-OVS DataPath

The Cisco ACI CNI plugin for Red Hat OpenShift Container Platform leverages a fully distributed data path implementation for all networking features implemented. The data path involves both software and hardware forwarding elements, optimally combined to ensure that no communication flow is penalized in throughput or latency.

All Pod traffic is received and processed first on Open vSwitch, which acts as kind of open virtual leaf of the fabric by means of the opflex agent controlling it. We have seen before that the Cisco ACI CNI plugin creates the virtual Ethernet interface for the Pod IP network namespace and connects it to an OVS Bridge.

The opflex OVS implementation leverages two different bridges to implement different features: br-access and br-int. Pod virtual Ethernet interfaces are connected to the br-access bridge. This is shown in Figure 67, where we highlight one of the NGINX Pods from previous example as seen on the APIC GUI and the diagram that shows how it is connected to the br-fabric. The same figure also shows, for reference, one of the Pods implementing the ingress routers.

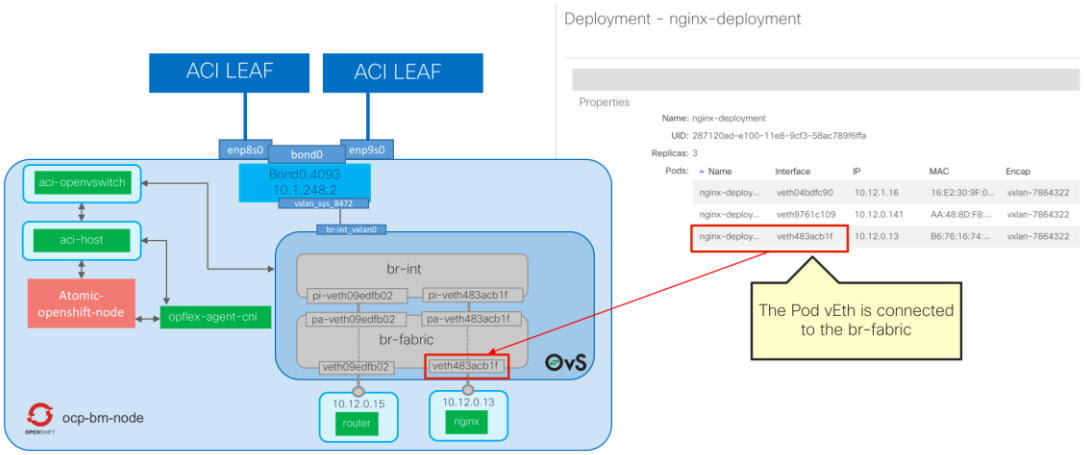

Figure 68: Detail of the Bridge and patch configurations on OVS

The virtual Ethernet interface of every Pod is connected back to the br-int by means of patch interfaces, also shown in Figure 67.

These two bridges are used to provide a clean separation of the implementation of opflex-programmed features. Specifically, br-int is programmed to implement routing, switching, load balancing and fabric contracts, while br-access is programmed to implement Host Protection Profiles that provide the distributed firewall to run Network Policies.

The opflex agent learns from APIC, through the opflex proxy on the leaf, what configuration is required including the EPG encapsulation, default gateway, contracts and HPPs and programs them on the respective Bridge. This is transparent to both OpenShift and fabric administrators, however it is important for troubleshooting purposes. Specifically, it's important to remember that HPP are installed in br-access while contracts are programmed on br-int. This also means that when traffic is originated on a Pod, NetworkPolicy is enforced first and contracts second.

6. Cisco ACI CNI Plugin for OpenShift Design and Use Cases

6.1. Namespace Segmentation, Application Segmentation and Security

Options

OpenShift Projects use Kubernetes namespaces to allow different users to share a single cluster. It is a common requirement that applications running on a given namespace should not by default be able to communicate with applications running on other namespaces, commonly referred to as namespace isolation.

The Cisco ACI CNI plugin offers various alternatives to implement segmentation for OpenShift applications. This includes making use of Network Policy objects to provide namespace or application-tier segmentation as well as using EPGs for segmentation.

6.2. Using EPGs for Cluster Level Isolation

The default installation mode of the ACI CNI plugin implements cluster-level isolation by placing all Pods from a given cluster in the kube-default EPG on the ACI fabric tenant provided for the cluster at installation time. This means that user Pods are by default isolated from Pods from other clusters as well as from infrastructure components since Pods can only access the node IP addresses (on kube-node EPG) by means of the specifically configured contracts. Workloads on the kube-default EPG can communicate with other fabric endpoints by defining additional contracts.

The OpenShift router also runs on the kube-default EPG and is exposed externally by the LoadBalancer service implemented using ACI Policy Based Redirection.

Within the kube-default EPG there are no restrictions for communication between Pods. However, if more granular segmentation is required between the Pods running within kube-default EPG, it is possible to define OpenShift Network Policy objects that is

implemented by the ACI CNI plugin as explained earlier in the document.

A common use case is to use NetworkPolicy objects to isolate different namespaces, as illustrated in Figure 68. All Pods are connected to kube-default EPG regardless of their namespace. Services can be exposed using OpenShift routes through the OpenShift router which is itself exposed via a LoadBalancer service using PBR.

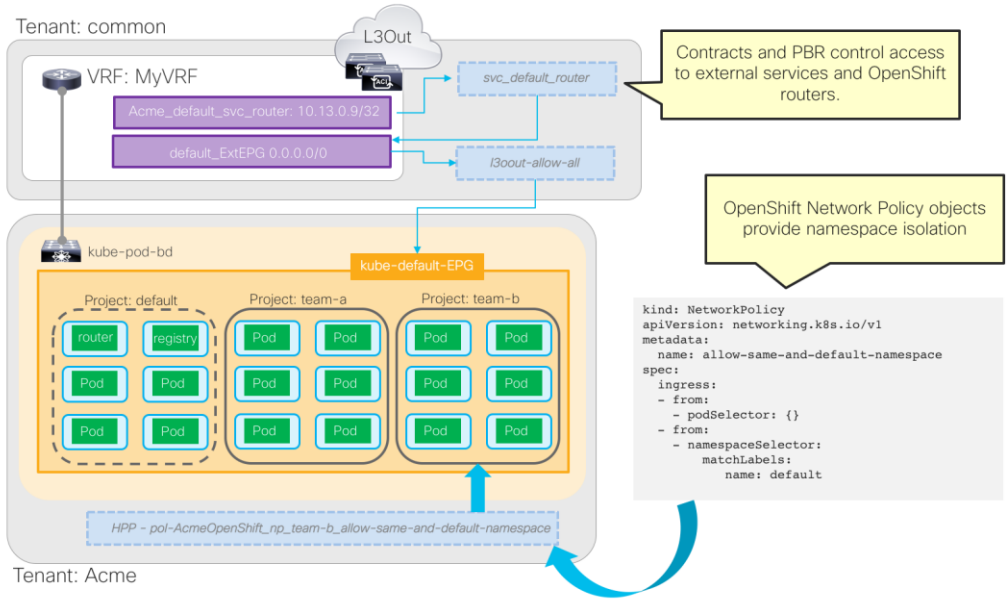

Figure 69: Using EPG for a cluster and NetworkPolicy for namespace segmentation

Other than the default project, two projects are shown: team-a and team-b correspond to Pods that belong to different teams. A NetworkPolicy object is configured on each project in order to allow communication within the project and from the default namespace project. It is important to maintain communication from the default namespace in order for the OpenShift router to be able to communicate with Pods on the user namespaces. When the NetworkPolicy object is applied, for instance to the team-b project/namespace, a Host Protection Policy is created on the ACI tenant. This HPP is implemented on Open vSwitch and applied to Pods that match the policy selector: in the example this is all Pods on team-b project/namespace.

It is also possible to add more granular policies within or between namespaces of course. The important aspect to understand is that in this model all policy that applies within the cluster is defined using OpenShift semantics and configuration options. The APIC ensures

the policies are implemented with a stateful distributed firewall and offers the fabric administrator visibility of the configured policies.

6.3. Using EPGs for Project Level Isolation

Using OpenShift Network Policy objects, it is possible to provide extremely granular levels of isolation, but these depend always exclusively on the configurations of the OpenShift administrators. For security and compliance purposes, it may be desirable to ensure that different projects are isolated from one another and that communication between them cannot be achieved directly without having privileges beyond the OpenShift cluster. Using the ACI CNI plugin it is very easy to achieve this objective by leveraging the native segmentation and security capabilities of the fabric.

To achieve project-level isolation, you must be creating a new EPG for every new OpenShift Project. In Figure 69, we show a possible design with an Application Profile for OpenShift Projects and two EPGs for two different OpenShift projects, one for Team-A and another for Team-B.

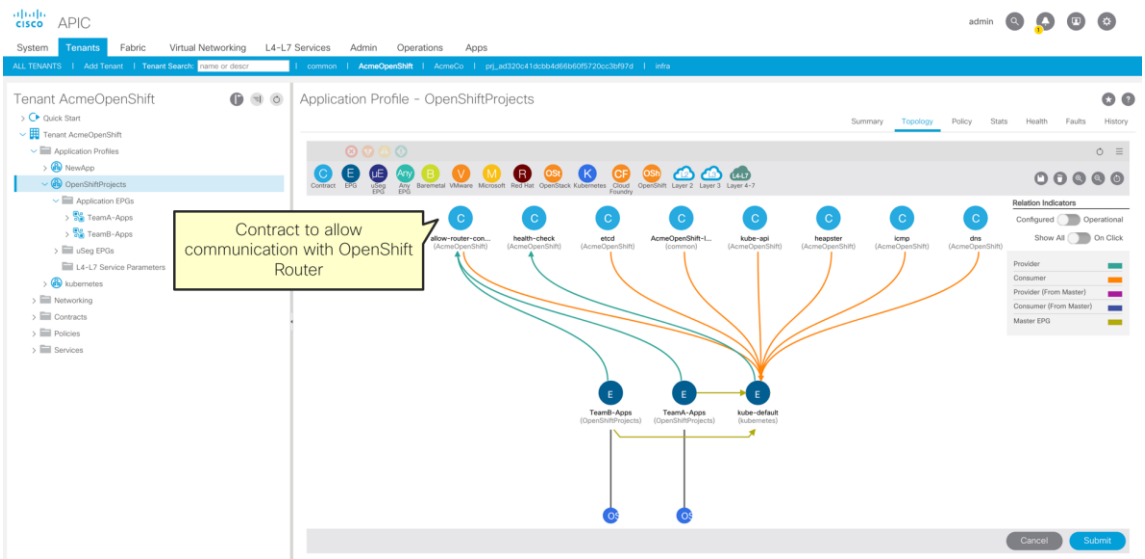

Figure 70: Using EPGs for OpenShift project segmentation

At the time creation, the OpenShift project must be annotated to use the right EPG. This can be done in a number of ways, for instance using the 'oc' CLI as shown below:

```
oc annotate namespace team-a opflex.cisco.com/endpoint-
group='{"tenant":"AcmeOpenShift","app-
profile":"OpenShiftProjects","name":"TeamA-Apps"}'

oc annotate namespace team-b opflex.cisco.com/endpoint-
group='{"tenant":"AcmeOpenShift","app-
profile":"OpenShiftProjects","name":"TeamB-Apps"}'
```

Figure 71

Once this is done, all Pods created within each project are on a dedicated EPG and are only able to communicate with other projects if an ACI admin establishes ACI contracts to do so. As shown in Figure 71, the EPGs for each project need to have associations to the contracts that allow OpenShift to function and the easiest way to ensure that is to configure them to inherit contracts from kube-default. An additional contract must be created between the kube-default EPG and the new EPGs to allow connectivity between the OpenShift router and the project/namespace Pods.

When using this model, it is important to plan for the event when a project is not annotated, because in that case its Pods are placed on the kube-default EPG. Since the OpenShift router is on the Default project and is running on kube-default EPG, those non-annotated projects are able to expose routes through the OpenShift router. For this reason, it is a good idea to define an EPG dedicated for the Default OpenShift project and to annotate that project to be outside of the kube-default EPG. In this manner, the OpenShift router is no longer on kube-default EPG and if a project is defined without the right annotations, its Pods are completely isolated.

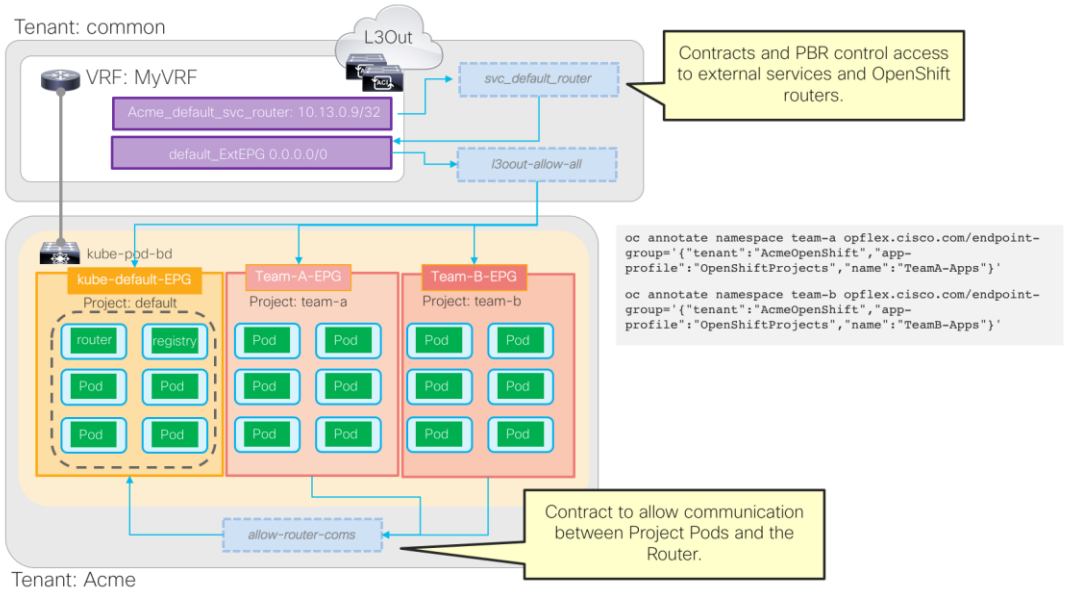

Figure 72: Using EPGs for OpenShift project segmentation

If communication is required between projects, contracts must be defined to allow for this communication to happen. Of course, within a given project's EPG, it is still possible to use NetworkPolicy to define more granular segmentation down to the application tier.

6.4. Using EPGs for Application Tier Isolation

It also possible to define EPGs for specific application tiers within a given project by using the annotations model. Again, in this case a prevision must be taken for the eventuality that a non-annotated Pod could end in the wrong EPG. Just like explained before, it is best to create an EPG for the 'default' namespace so that the OpenShift routers are placed there, thus leaving kube-default as a catch-all for non-annotated Pods to be isolated. Then an application profile can be defined for each OpenShift project and within the application profile, an EPG for each Deployment Config.

This model is depicted in Figure 72. In that picture the default namespace is still on kube-default EPG, but we show a two-tier application with a frontend tier and a Redis database tier each having its own EPG. The Pod templates used to build each tier must be annotated to the right EPG. This allows for granular contract usage so that communication between tiers is whitelisted with contracts and also only the tier that requires to expose routes has access to the OpenShift routers.

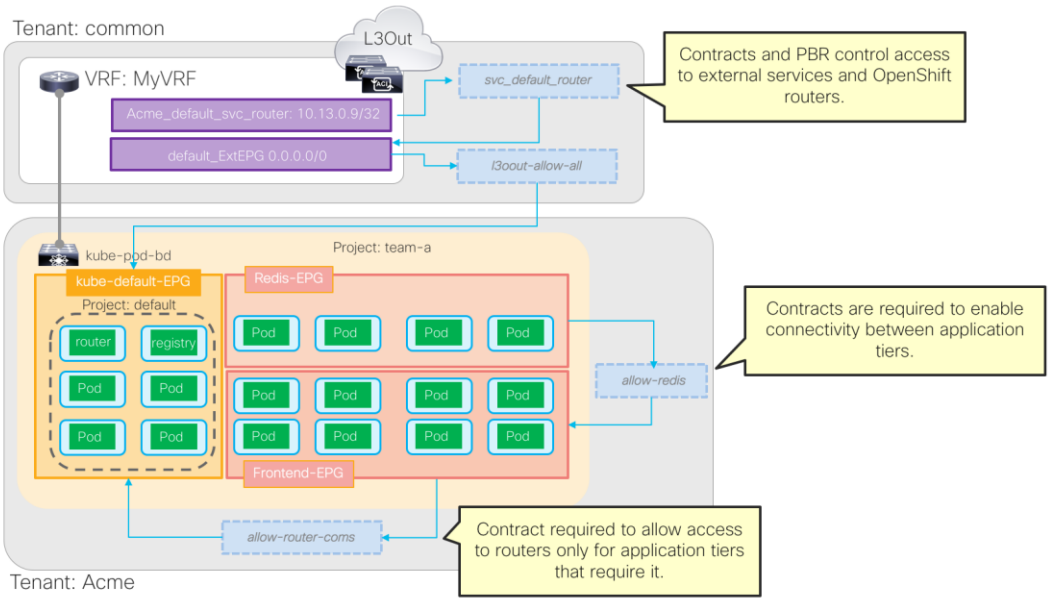

Figure 73: Using EPGs for OpenShift application segmentation

As in previous examples, the use of EPG and contracts for segmentation does not prevent complementing it with the use of NetworkPolicy objects, but it does mean that the policy can be controlled completely by administrators outside of the OpenShift cluster if that is required.

6.5. Enhancing the Kubernetes Application Profile for OpenShift

The default Kubernetes application considers only the basic contracts to let a cluster function. Red Hat OpenShift Container Platform allows administrators to install many additional functions, some of which run on its own dedicated namespaces.

For example, OpenShift can use Hawkular and Heapster to collect metrics. These services are deployed on the Project OpenShift-infra. Another example is the OpenShift Web Console, which is deployed to OpenShift-web-console project.

It is a good practice to define EPGs for each of these infrastructure namespaces and annotate the namespace/project in order to place all Pods in their respective EPGs. This can be convenient for various reasons. First, to ensure that user Pods cannot directly access these infrastructure Pods. Second, by having infrastructure Pods in dedicated EPGs, the fabric admin can have better visibility in APIC for these services.

In Figure 73 we show an example of the Kubernetes application profile with some additional EPGs and contracts. New EPGs have been defined for the kube-service-catalog, OpenShift-infra and OpenShift-web-console OpenShift projects. It is important also to add a contract that allows port tcp/10250 for Heapster to work between the kube-nodes EPG and any EPG having Pods monitored by Heapster.

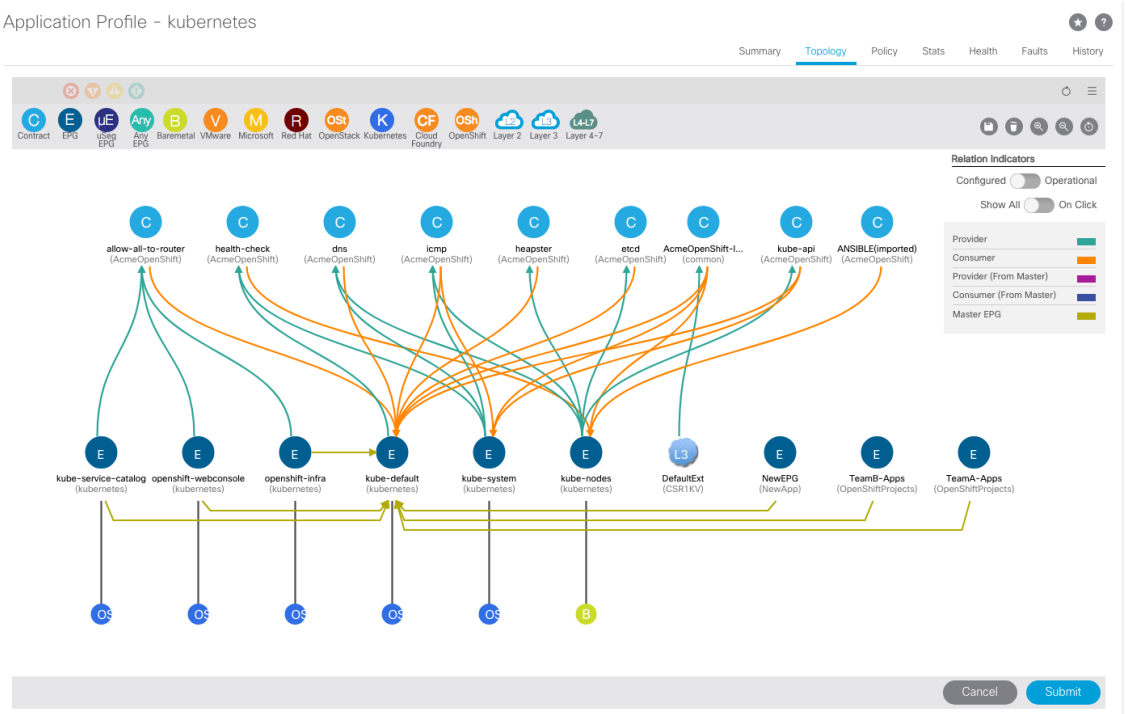

Figure 74: Using EPGs to segment OpenShift infrastructure projects

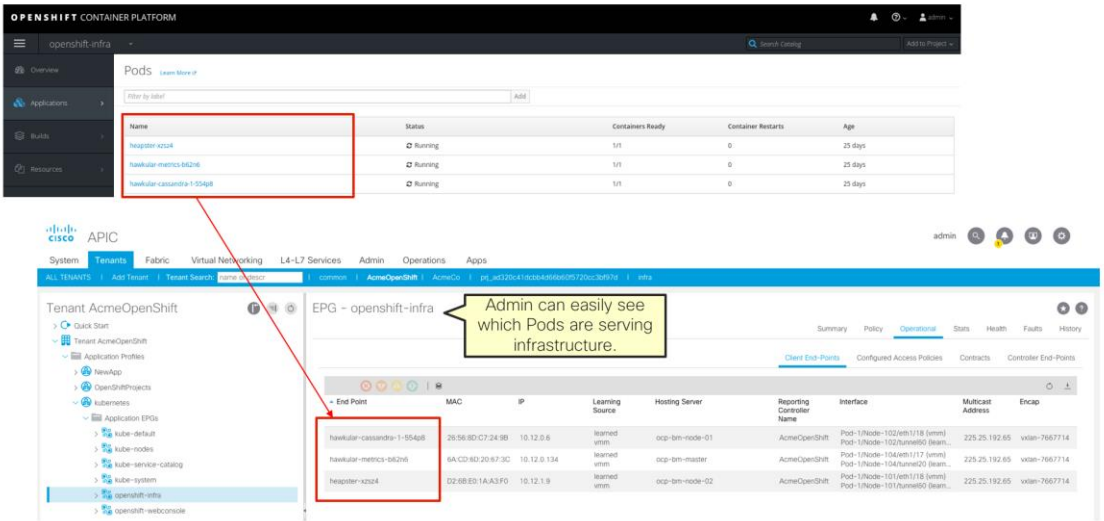

Figure 75: Pods on OpenShift-infra project isolated on its own EPG

6.6. Eliminate the need for Egress Routers

A common problem of using network overlays is that gateways are required to allow connectivity between endpoints in the overlay and endpoints outside of the overlay. For exposing services to external endpoints, we have seen in the previous section that the OpenShift router can provide an entry gateway.

However, a gateway is traditionally required also for egress traffic. We define "egress traffic" here not as traffic that is sent out of the cluster as a response to a connection from external endpoints, but as Pod traffic that initiates a connection to external endpoints. When using the native OpenShift SDN options, an egress router function is provided. This works by essentially designating a node to act as the egress gateway and NAT all traffic out of the cluster. This solution presents three challenges:

1. It funnels all egress traffic through one node, adding latency and introducing a performance bottleneck.
2. If the node selected fails, traffic is black holed until a new node can be made available.
3. Traffic must be NAT'ed outside of the overlay. This means that all traffic from a namespace (or even from a cluster) is seen as one IP Address.

While there's been enhancements since OpenShift 3.10 in terms of availability, such as "HA namespace-wide egress IP" or automatic namespace-wide egress IP, use of egress routers represents a challenge for applications requiring high-speed, low-latency access from the cluster to external endpoints.

When using the Cisco ACI CNI plugin, OpenShift Pods connect to the same integrated overlay as any other workloads. This means that there is no need to have gateways to establish connectivity between any OpenShift Pod and any other fabric endpoint, be it a Virtual Machine, a Bare Metal server or another Pod from another cluster. This has the following advantages compared to using egress routers:

1. Traffic is routed from every node via the optimal path to the destination, offering lowest possible latency and highest throughput. There are no bottlenecks.

2. Because no gateways are required, the solution is inherent highly available.
3. By leveraging EPG annotations down to the application tier level it is easy to have very granular control about which Pods can access which external services without requiring NAT.

When using the Cisco ACI CNI plugin every Pod is connected to the fabric's integrated VXLAN overlay as much as every other endpoint. This means that the fabric can route traffic between any Pod and any other fabric endpoint. Using EPGs and contracts it is possible to restrict connectivity very granularly. In Figure 75, we show a configuration where an OpenShift cluster is using subnet 10.12.0.1/16 for Pod IP addresses configured on kube-pod-bd. We also show another BD, called legacy-bd with subnet 172.16.1.1/24. The fabric knows how to route between the two Bridge Domains. A fabric or security administrator, or an automation system with the equivalent responsibilities can configure a contract to allow connectivity between an EPG mapped to the OpenShift VMM domain and an EPG mapped to any other domain, in the example a Physical Domain for Bare Metal.

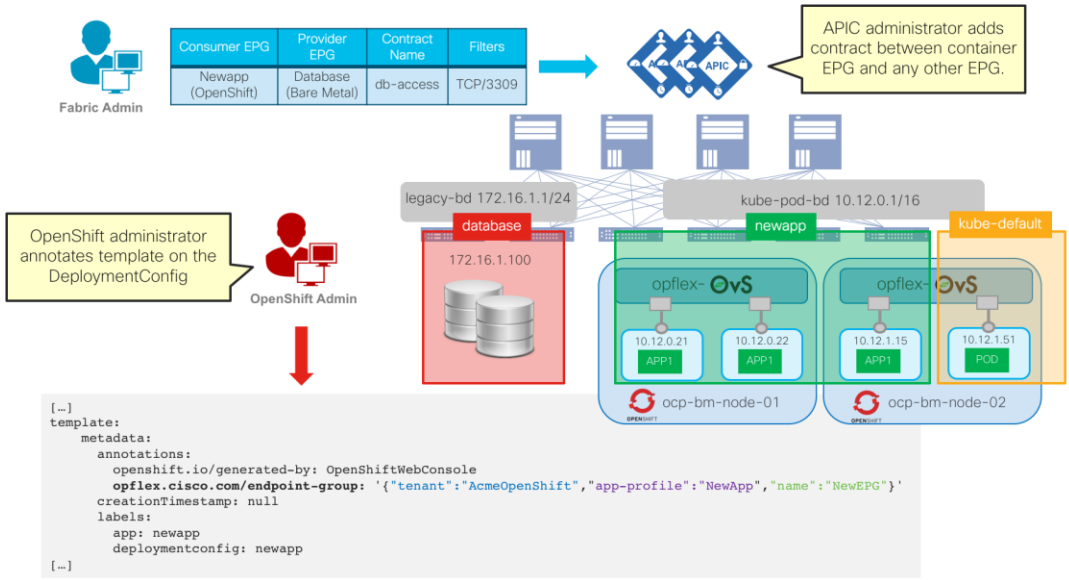

Figure 76: A template is annotated to place Pods from a Deployment Config on NewEPG

The OpenShift administrator or developer can edit the Deployment Config YAML, as seen in the figure, to ensure that all Pods of the 'newapp' are connected to the EPG that has access to the baremetal database.

The ACI CNI plugin connects all Pods that are part of the Deployment Config to the right EPG. In addition, the opflex agent also programs the ACI contracts on Open vSwitch, just

like it does for Network Policy. Therefore, as seen in Figure 76 all Pods on the 'newapp' EPG have access to the database. Pods in other EPGs, such as kube-default, do not have access.

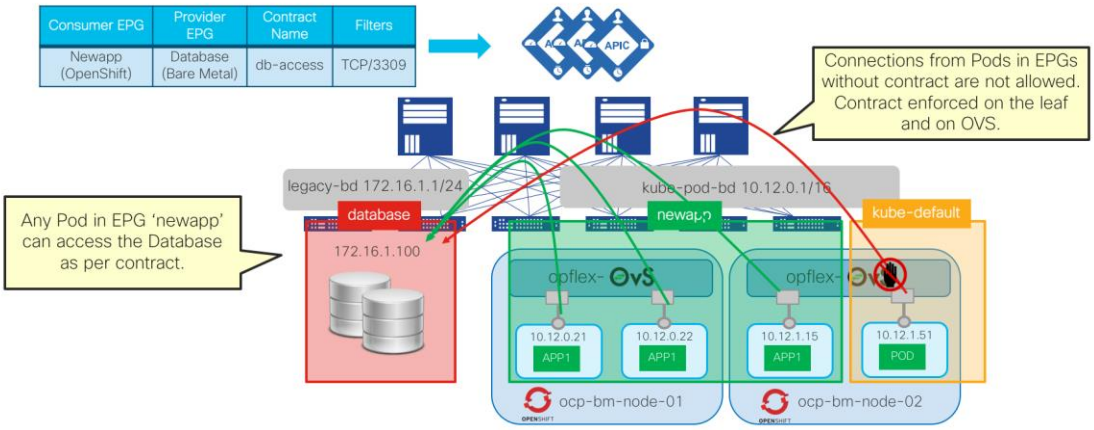

Figure 77: Pods part of newapp deployment config can access the DB because of the configured contract

As seen on the illustration, traffic from each of the OpenShift nodes is routed to the destination database directly if allowed by the contract. There is no need to send the traffic to an egress router, nor is there a need to NAT it because all endpoints are known to the ACI fabric.

It is also possible to combine this model with ACI Service Graphs in order to have the traffic between the OpenShift cluster and EPGs mapped to Bare Metal, VMware, Microsoft or Red Hat Virtualization VMM domains be filtered by a Next Generation Firewall.

6.7. L3Out Options

L3Out interfaces specify how an ACI fabric connects with external routed networks. An L3Out interface can span multiple leaf switches and can use both static and dynamic routing protocols to advertise the fabric's local subnets and to learn external ones.

Apart from learning how to route to external prefixes, L3Out interfaces have associated "Network" objects (`InstP` in the object model) which are referred to as External EPGs. Similar to regular EPGs, they specify a group of endpoints that require the same policy for communication. In the case of External EPGs, the endpoints are specified by defining them via CIDRs.

Every OpenShift cluster using the ACI CNI plugin requires access to an L3Out interface for at least two purposes:

1. It is expected that the OpenShift nodes require access to external repositories and/or registries that are not connected to the fabric.
2. Services exposed outside of the cluster are modelled in ACI as external EPGs associated to the L3Out.

6.8. Single VRF, L3Out, and Multiple Clusters

A single VRF can be shared by many OpenShift clusters if it is placed in the common tenant in ACI. It is possible to use a single L3Out in the common tenant to provide connectivity to all the clusters external services as well as node and pod IP addresses.

No special configuration is required on the Cisco ACI CNI side.

Each OpenShift cluster can use a dedicated L3Out and VRF, configured on the tenant where the OpenShift cluster's Kubernetes application is defined.

6.9. Multiple OpenShift VRFs and Tenants with Shared Common L3Out

Note: This configuration is supported as of Cisco ACI CNI release 4.0(2.20181221).

Each OpenShift cluster is deployed in a dedicated tenant with its own VRF. It is possible to use a single L3Out in the common tenant to provide external connectivity to all the OpenShift tenants. The common L3Out uses a dedicated VRF, and the Cisco ACI fabric performs route leaking as required.

In order for this configuration to work the following configurations must be applied:

- When you create external services on OpenShift, annotate them with the annotation: "opflex.cisco.com/ext_service_contract_scope=Global". This annotation instructs the Cisco ACI CNI plug-in to configure the contract scope to global to ensure the Service Graph will allow inter-VRF traffic.
- Mark the pod and node subnets under the bridge domain with the "shared between VRFs" flag to allow that the routes are leaked.

The following figure shows an example of logical configuration:

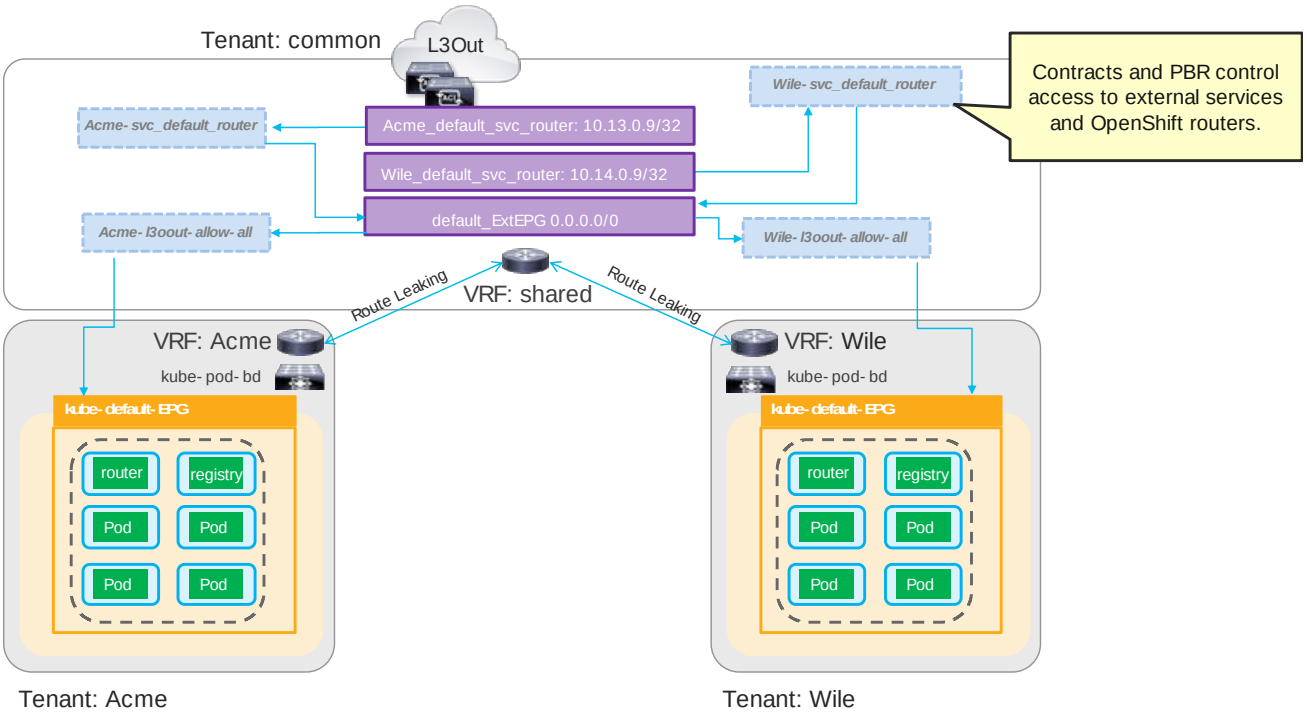

Figure 77: Logical configuration of Multiple OpenShift VRFs and with Shared Common L3Out

7. Exploring the 'Nested-Inside' Deployment Option

7.1. Introducing the nested-inside acc-provision parameter

It is possible to run OpenShift nodes (controllers and compute nodes) as virtual machines hosted on a VMware vSphere cluster. This becomes particularly interesting when networking for that vSphere cluster is managed by APIC through a VMware VMM domain. Covering how to integrate ACI and VMware is outside the scope of this document; we assume the reader is familiar with how to achieve this configuration. If not, refer to https://www.cisco.com/c/en/us/td/docs/switches/datacenter/aci/apic/sw/3-x/virtualization/b_ACI_Virtualization_Guide_3_0_1/b_ACI_Virtualization_Guide_3_0_1_chapter_011.html for more details. Be aware that acc-provision does not create the VMware VMM on your behalf; it needs to pre-exist before running acc-provision, exactly like the L3Out configuration.

Assuming you have a VMware VMM domain on APIC, you can connect OpenShift virtual

nodes to a DVS managed by APIC. The acc-provision utility provides a configuration setting that lets APIC create VLAN trunking port-groups on the DVS with the appropriate VLANs extended for your OpenShift with ACI environment. You need to provide two parameters to acc-provision:

1. The type and name of the VMware VMM domain your OpenShift virtualized nodes reside. For type, use 'vmware'.
2. The AEP that is used by your vSphere hosts to gain fabric connectivity.

This is shown below:

```
#
# Configuration for ACI Fabric
#
aci_config:
  system_id: openshiftpeg2       # Every opflex cluster must have a distict ID
  apic_hosts:                    # List of APIC hosts to connect for APIC API
  - 10.48.168.2
  vmm_domain:                    # Kubernetes container domain configuration
    encap_type: vxlan            # Encap mode: vxlan or vlan
    mcast_range:                 # Every opflex VMM must use a distinct range
      start: 226.30.1.1
      end: 226.30.255.255
    nested_inside:
      type: vmware
      name: PEG2-DC1

  aep: ESXi-RM9                 # The AEP for ports/VPCs used by this cluster
  vrf:                           # This VRF used to create all kubernetes EPs
    name: default
    tenant: common               # This can be system-id or common
  l3out:
    name: SharedL3Out           # Used to provision external IPs
    external_networks:
    - internet                   # Used for external contracts
```

Name of your VMware VMM domain

AAEP used by that VMM domain's ESXi hosts

Figure 78

After you have configured these parameters, run acc-provision just like you normally would. This time though, you see a new port-group on the DVS managed by APIC:

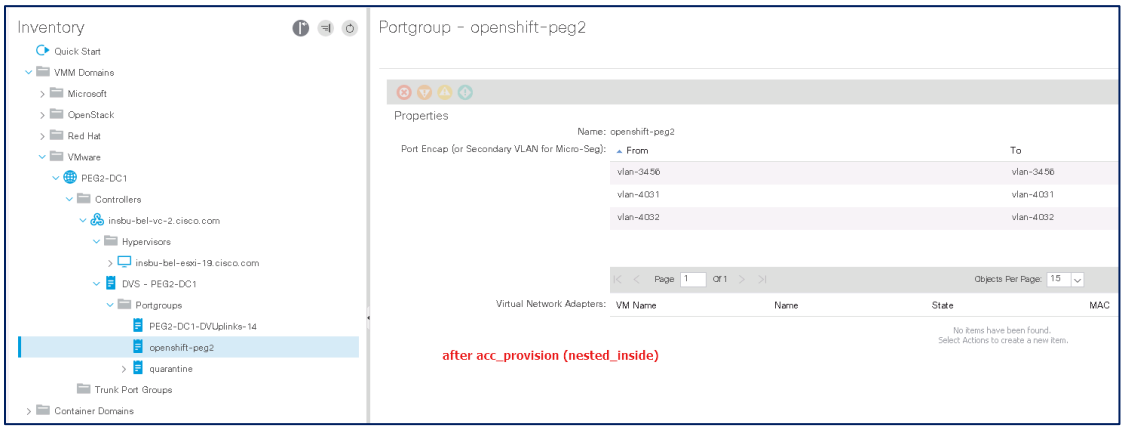

Figure 79

That port-group is named after your system_id. In the picture above, a small discrepancy exist between openshiftpeg2 and openshift-peg2, ignore it – hyphens are no longer accepted for system_id in recent versions of acc-provision. The port-group is of the trunking type and carries three VLANs:

1. ACI infra VLAN
2. VLAN for your OpenShift/K8s nodes (maps to the node-BD and EPG)
3. Service VLAN (for PBR services as explained above)

All you have to do now is attach the virtual NICs of your OpenShift virtualized nodes to that port-group and configure the OpenShift virtualized nodes as if they were bare-metal nodes. Create the appropriate VLAN interfaces on your nodes and assign IP addresses to them. Verify your nodes can ping the node BD and you're on your way! One caveat worth mentioning with nested-inside is that you can't vMotion the virtual OpenShift nodes; doing so results in loss of connectivity.

Annex A. Proposed Ansible Approach for Creation of Annotated EPGs

As covered in this document, you may place Pods inside specific EPGs on ACI using annotations. You probably recall that the EPG needs to pre-exist in that case because the CNI plugin has no capability to create EPGs on the fly. Once you create the desired EPGs, you also need to add the necessary contracts for ensuring your Pods can talk to the HAproxy router, to etcd and other services. Automating the creation of those contracts and EPGs is a straightforward matter with an automation tool such as Ansible. Other methods can be used of course – we are simply suggesting a playbook to achieve this result.

You could call the playbook below with a command-line parameter as follows:

ansible-playbook -i your_inventory.ini aci-create-epg.yaml --extra-vars "epgName=<name>"

```
---
- name: create EPG for Openshift annotated namespace
  hosts: apic
  connection: local
  vars:
    epgName: '{{ epgName }}'
  tasks:
  - name: create EPG in existing Openshift tenant
    aci_epg:
      hostname: 10.10.10.10
      username: sdn
      password: cisco
      tenant: openshiftpeg2
      ap: annotated
      epg: '{{ epgName }}'
      description: Ansible
      bd: kube-pod-bd
      use_ssl: yes
      validate_certs: no
      use_proxy: no
```

```
- name: Add a new contract to EPG binding
  aci_epg_to_contract:
    host: 10.10.10.10
    username: sdn
    password: cisco
    tenant: openshiftpeg2
    ap: annotated
    epg: '{{ epgName }}'
    contract: '{{ item.name }}'
    contract_type: '{{ item.status }}'
    state: present
    use_ssl: yes
    validate_certs: no
  with_items:
    - { name: 'etcd', status: 'consumer' }
    - { name: 'dns', status: 'consumer' }
    - { name: 'icmp', status: 'consumer' }
    - { name: 'default', status: 'consumer' }
    - { name: 'openshiftpeg2-l3out-allow-all', status: 'consumer' }
    - { name: 'kube-api', status: 'consumer' }
    - { name: 'health-check', status: 'provider' }

- name: Bind EPGs to Domains on Cisco ACI fabrics (fv:RsDomAtt)
  aci_epg_to_domain:
    ap: annotated
    domain: openshiftpeg2
    domain_type: vmm
    epg: '{{ epgName }}'
    hostname: 10.10.10.10
    password: cisco
    state: present
    tenant: openshiftpeg2
    use_proxy: no
    use_ssl: yes
    username: sdn
    validate_certs:
    vm_provider: openshift
```

When the playbook has executed, create a new namespace and annotate it as shown below:

```
oc annotate namespace <name>
opflex.cisco.com/endpoint-group='{"tenant":"openshiftpeg2","app-profile":"annotated"
,"name":"'<name>'"}'
```

Pods created in that namespace automatically appear under the annotated/<name> EPG now.