Understanding the Kubernetes Networking Model

Understand the container networking model in Kubernetes.

We'll cover the following

Overview

In Kubernetes, the CNI is seamlessly integrated with `kubelet` to allow configurable networks between Pods. The network could be overlay or underlay. The **overlay network** encapsulates the network traffic using a virtual interface like `VxLan`, while the **underlay network** works at the physical layer composed of switches and routers. This decoupling gives us more freedom to choose appropriate network solutions and keeps the Pods portable to heterogeneous infrastructures.

No matter what the underlying infrastructure or network is, the Pods are accessible and can communicate with each other. Before we dive into how the CNI works, it's worth discussing the Kubernetes networking model. This model is not only a design philosophy, but also has a close relationship with the CNI.

The Kubernetes networking model

As we know, the smallest deployable and schedulable unit is a Pod. One or more containers are grouped into one Pod. Such a design can support multiple cooperating processes for a cohesive unit called a Service. Each process runs in a separate container. Multiple containers serve as a standalone Service or application.

These applications share all the resources in the Kubernetes cluster, including the CPU, memory, and network. However, we can't run applications with the same port on the same node. This is physically impossible. Typically, we need to ensure that two applications on the same node are using nonconflicting ports. Using dynamic port allocation brings a lot of complications, such as how to assign ports dynamically on each node under high concurrency, how to notify other service consumers on the ports, how to maintain the configuration blocks on the changing dynamic port numbers, and so on. To solve these complications, Kubernetes takes an opinionated approach to container networking. In particular, Kubernetes strictly stipulates that any network implementations should follow the guidelines below.

- Every Pod gets its own IP address. The IP address that a Pod sees itself as is exactly the same IP that other Pods see it as. This is the most important and fundamental design philosophy in the Kubernetes networking model. Moreover, this IP is unique in a whole cluster. All the containers of this Pod share this IP. They can run with different ports. To achieve this IP sharing for multiple containers in a Pod, there is a **pause container** (also called a **sandbox container**) for each Pod. This pause container's purpose is to hold a network namespace (`netns`), which is shared by all the other containers in this Pod. In this way, the IP address of a Pod doesn't change even if containers are killed and recreated in place. This is the so called `IP-per-Pod` model.
- Pods can use Pod IP addresses to communicate with all other Pods on other nodes without network address translation (NAT).
- Agents (such as system daemons, `kubelet`, etc.) on a node can communicate with all the Pods on it.

Networking scenarios in Kubernetes

The Kubernetes networking model is concerned with the following four networking scenarios:

- Container to container communications
- Pod to Pod communication
  - Intra-node communication
  - Inter-node communication
- Service to Pod networking
- External to cluster communication

Let's see how these four scenarios fit in with the Kubernetes networking model.

Container to container communication

In Linux, each running process communicates within a network namespace, which provides a logic networking stack, including routes, firewall rules, and network devices. All the processes within the namespace share the network stack. With the following command, we can create a new network namespace `ns1`:

```
ip netns add ns1
```

Create a network namespace

Once the namespace is created, a corresponding mount point for it is created under `/var/run/netns`, where the namespace is persisted even if we have no processes attached to it.

```
ls /var/run/netns
# or we can run
ip netns
```

List available network namespaces

We can list the available network namespaces by running the commands above in the following terminal:

Terminal 1

Terminal

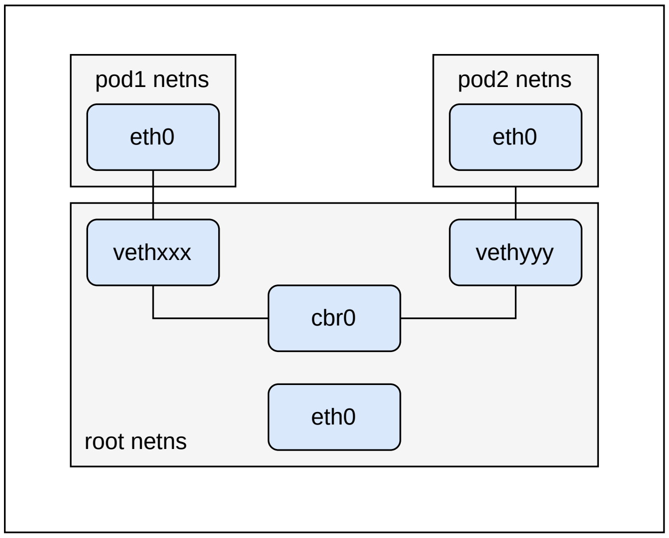
Click to Connect...

In Linux, every process is attached to the root network namespace by default. The main network interface `eth0` is in this root network namespace. Similarly, every Pod has such a self-owned network namespace. Containers within a Pod share the network namespace, such as the IP address, ports, etc. They can communicate with each other via the `localhost` since they reside in the same network namespace.

Intra-node Pod to Pod communication

Making sure Pods running on the same node can talk to each other is essential so that we are able to extend the communications across nodes, to the Internet, etc.

Every `kubelet` node has a designated CIDR range for the Pods running on it. This helps make sure that the Pods never have overlapping IP addresses. Every Pod has its own Ethernet namespace. To connect Pod namespaces, we can use a virtual Ethernet device or a `veth` pair, as the image below shows. We assign one side of the `veth` pair to the root namespace and the other side to the Pod network namespace. Such a `veth` pair pipes two virtual interfaces and allows network traffic to flow between them. To make Pods connective with each other, a virtual network bridge (e.g. `cbr0`) is used to connect these virtual interfaces. Moreover, Pods can communicate with each other through the root namespace using the Address Resolution Protocol (ARP).



Intra-node Pod to Pod communication

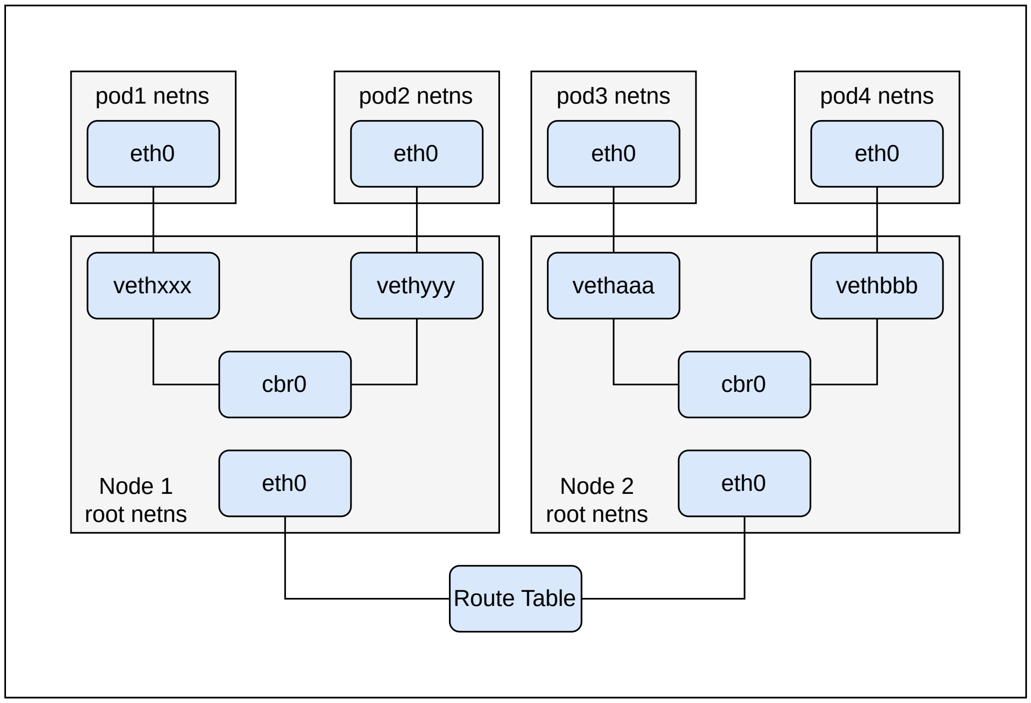
Thus, when we send a packet from `pod1` to `pod2`, the network flow is as follows:

1. The `pod1` traffic flows through `eth0` to the virtual interface `vethxxx` in the root network namesapce.
2. The traffic is then passed on to the virtual bridge `cbr0`, which resolves the destination using an ARP request saying "who has this IP?"
3. The virtual interface `vethyyy` says it has that IP, so `cbr0` knows exactly where to forward the packet.
4. When the packet reaches the virtual interface `vethyyy`, it is piped to the `pod2` network namespace `eth0`.

Inter-node Pod to Pod communication

In the Kubernetes networking model, Pods running on different nodes should be able to communicate with each other as well. As long as the traffic can reach the desired Pod running on the other node, Kubernetes doesn't care how we make it. Only if we can make sure each Pod has a unique IP that won't conflict with Pods on another node, we have multiple ways to do this, such as ARP across nodes (Layer 2), IP routing across nodes (Layer 3), overlay networks, etc.

Here, we've got two nodes, as the image below shows. A packet is going from `pod1` running on `node1` to `pod4` on `node2`.



Inter-node pod to pod communication

1. The packet leaves from `pod1` at `eth0` and directly enters the root `netns` at `vethxxx`.
2. It is then passed on to the virtual bridge `cbr0`, which sends an ARP request to find who owns the destination IP address.
3. On failure, the virtual bridge `cbr0` sends the packet out the default `eth0` device in the root network namespace. At this point, the packet enters the network.
4. Assuming that the network can route the packet to the target node based on the CIDR blocks to each node, it routes the packet to the node whose CIDR block has the `pod4` IP address.
5. Now, the packet arrives at `node2` at the main network interface `eth0` in the root network namespace. But how do we let the packet be forwarded to the virtual network bridge `cbr0`, since the interface `eth0` doesn't have the IP address of `pod4`? We need to configure the node with enabling IP forwarding, so that the packet will be forwarded to any routes matching the `pod4` IP. For now, it can find the virtual bridge `cbr0`.
6. The virtual bridge receives the packet and makes an ARP request that has the IP address of `pod4`. Finally, it finds out this IP belongs to `vethbbb`.
7. The packet flows across the pipe-pair and enters the network namespace of `pod4`.

Service to Pod communication

In Kubernetes, Pods are ephemeral, in that they can be scaled up or down on demand. They may also be deleted at any time. This makes it a challenge to get an unchanged endpoint for applications.

Kubernetes introduces a concept `service` to describe a group of Pods. With `service`, we can do the following.

1. We can assign a static virtual IP address that can be used for in-cluster accessing. This virtual IP address associates with multiple back-end Pods' IPs. The **Endpoints controller** (or the

EndpointSlice controller for Kubernetes with a higher version) takes care of the IP changes of matching Pods.
2. The traffic addressed to this virtual IP can be load balanced to the set of back-end Pods.

Normally, in-cluster load balancing occurs in two ways: iptables and ipvs. This part is handled by the `kube-proxy`. A series of routing rules will be created to interpret this virtual IP address to a matching back-end Pod.

External to service networking

In Kubernetes, we have multiple ways to expose our services for external accessing.

We can create a `service` with `type=LoadBalancer`, which is backed by external cloud providers. The cloud provider is responsible for provisioning a load balancer for this `service`. One of the most widely used methods for mapping this load balancer to back-end Pods is `NodePort`.

Using `Ingress` is another popular and recommended way to expose our services to the outside of the cluster. The `Ingress` controller acts as a reverse proxy and load balancer for HTTP and HTTPS. It intercepts all incoming requests to our cluster and routes to different services, based on the rules of the requesting path.

Conclusion

This networking model brings huge benefits. The network is simple to understand. We don’t need to worry about port conflictions for different applications, and it’s easier to migrate applications from one node to another. Pods can be treated as cattle for real.

There are also other aspects to Kubernetes networking, such as service-based load balancing, exposing internal services to outside, and so on. However, the role of the CNI is merely to facilitate the communications between Pods, regardless of which host they land on. This focus makes CNI specifications simple and widely adaptive to various container runtimes and infrastructures.

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Introduction to CNI

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