Load Balancer IP Pool Allocation

Claude Code Assistant

2025-10-01

Contents

1 Overview

The load balancer implements dynamic IP allocation from a CIDR range to support multiple Kubernetes services without manual IP assignment. When an IP address is already in use, the system automatically allocates the next available IP from the configured CIDR pool.

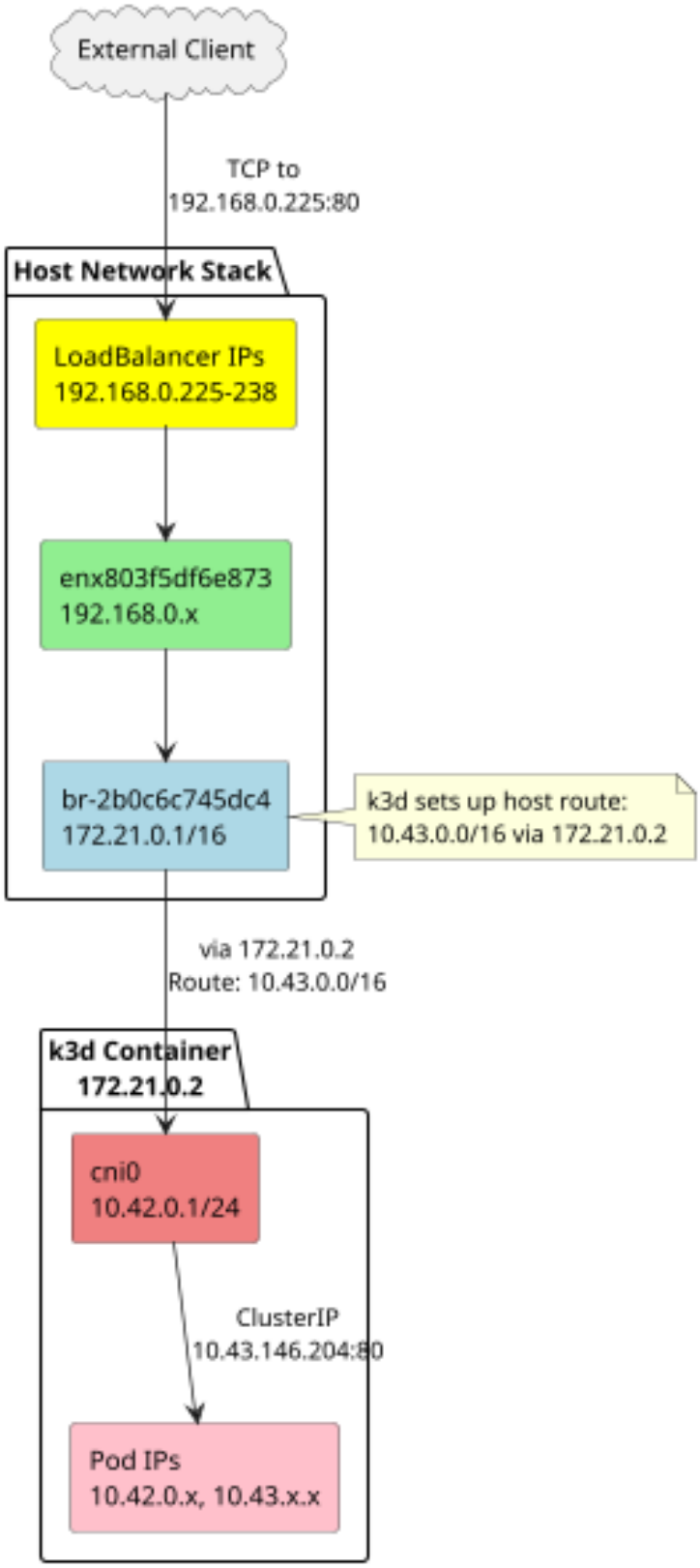
1.1 Diagrams in This Document

Diagram	File	Description
Network Architecture	network-architecture.png	Shows host/k3d network topology
Connection Flow	connection-flow.png	Sequence diagram of TCP proxy flow
Service Binding Flow	service-binding-flow.png	Activity diagram of IP allocation with retry
IP Lifecycle	ip-lifecycle.png	State diagram of IP allocation/release lifecycle

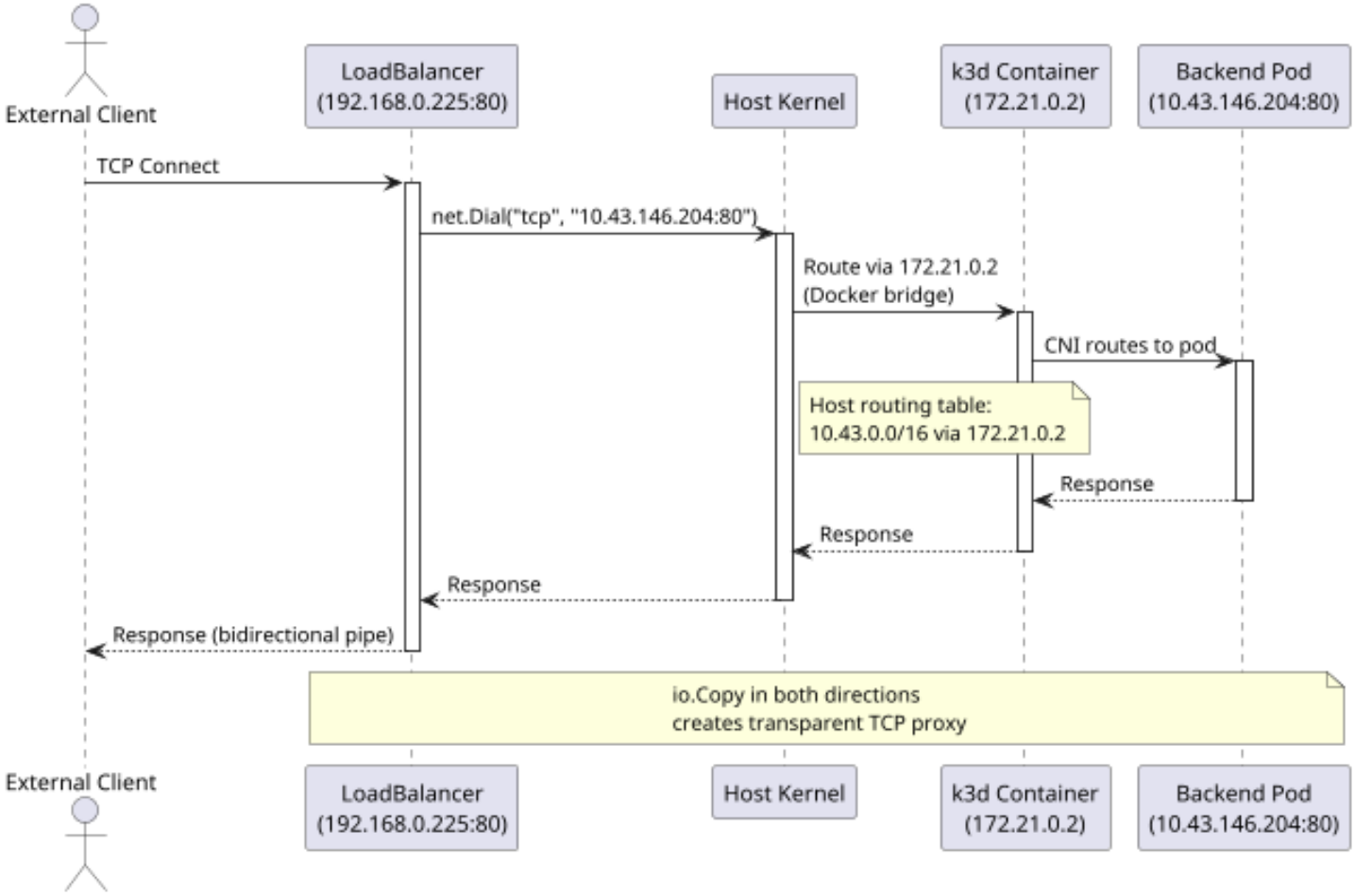
To generate diagrams, position cursor on each `#+begin_src plantuml` block and press `C-c C-c`.

2 Architecture

2.1 Network Architecture Diagram



2.2 Connection Flow Diagram



2.3 IP Pool Management

The IP pool manager maintains a thread-safe allocation table for IP addresses within a configured CIDR range. It tracks which IPs are currently allocated and provides methods for allocation and release.

2.3.1 Key Components

`IPPool` Thread-safe IP allocation manager

`IPPoolInstance` Global instance initialized from DefaultCIDR

`Allocate()` Returns next available IP from the pool

`Release(ip)` Returns IP to the pool for reuse

2.4 Location in Codebase

`ipmgr/cidr.go:154-230` IPPool type and methods

`ipmgr/defaults.go:38-39` Global IPPoolInstance variable

`mgr/ipmgrinit.go:105-111` IP pool initialization

`mgr/open.go:83-153` IP allocation with retry logic

`mgr/listener.go:384-395` IP cleanup on listener close

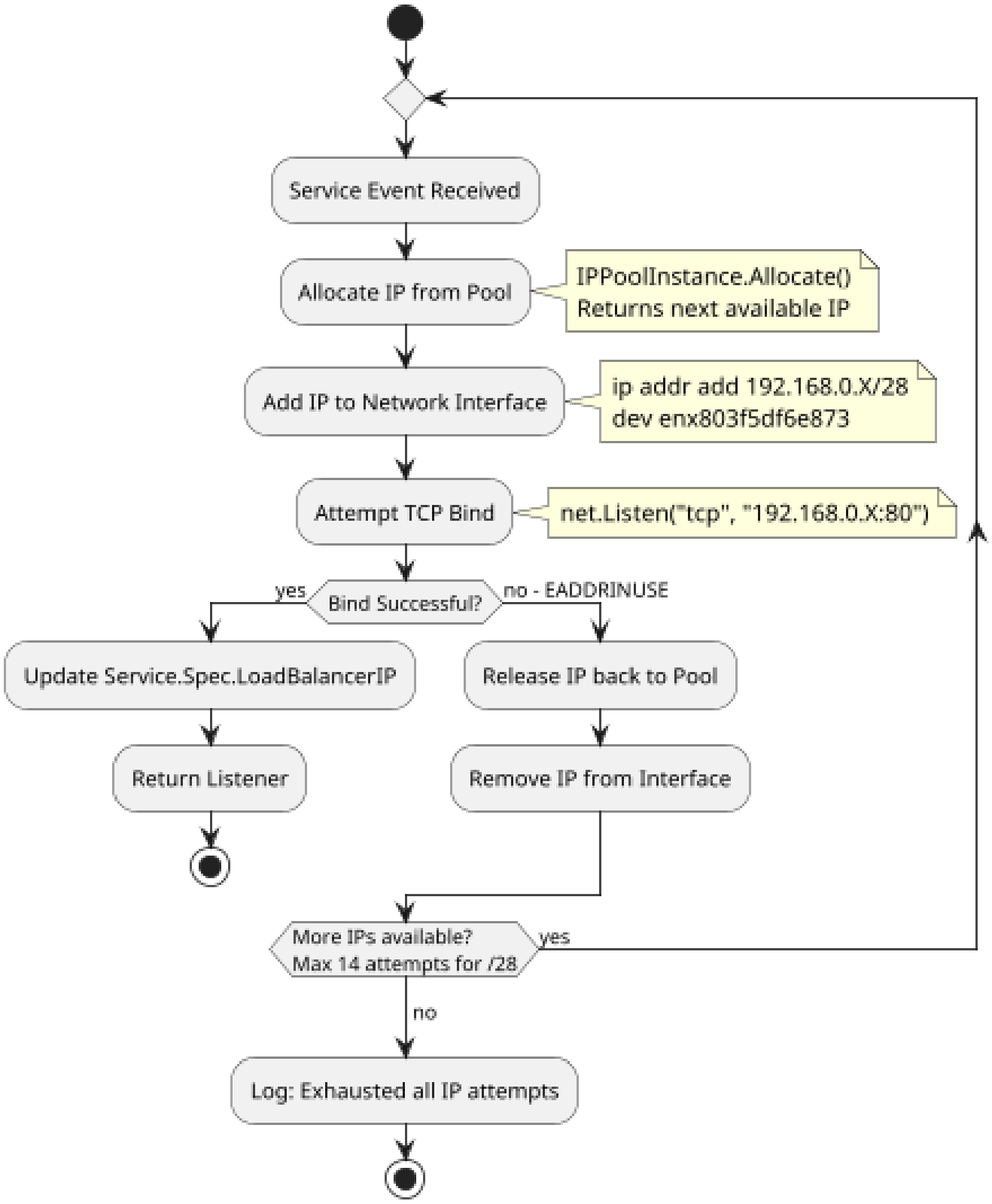
3 IP Allocation Process

3.1 Initialization

When the load balancer starts, it initializes the IP pool from the configured CIDR range:

```
// Initialize IP pool from the CIDR range
var err error
ipmgr.IPPoolInstance, err = ipmgr.NewIPPool(ipmgr.DefaultCIDR.String())
if err != nil {
    log.Fatalf("Failed to create IP pool from CIDR %s: %v",
               ipmgr.DefaultCIDR.String(), err)
}
log.Printf("Initialized IP pool for CIDR: %s", ipmgr.DefaultCIDR.String())
```

3.2 Service Binding Flow



3.3 Code Flow

3.3.1 ListenWithIPAllocation Function

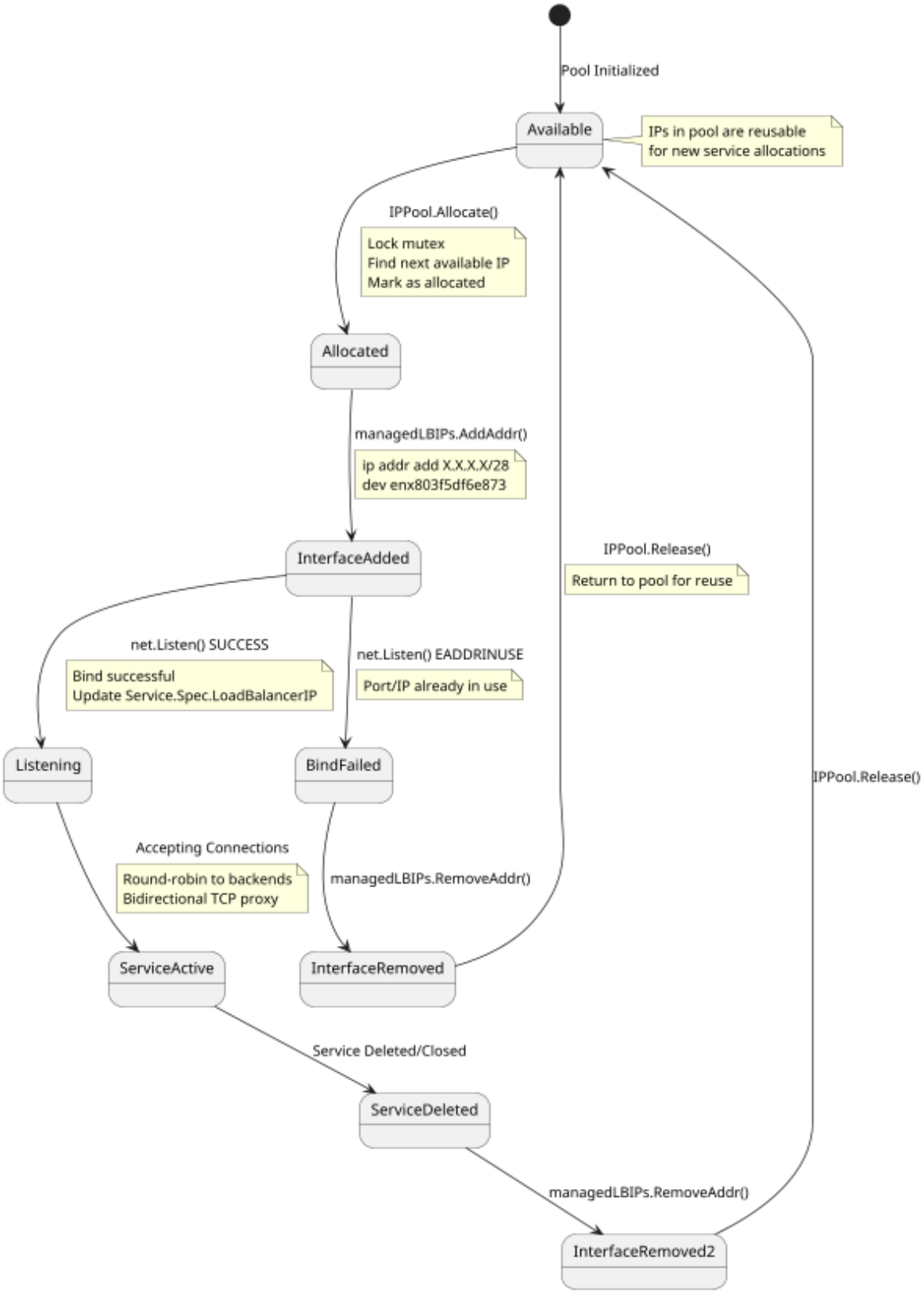
The `ListenWithIPAllocation` function in `mgr/open.go:83-153` implements the retry logic:

```
func ListenWithIPAllocation(serviceKey string, Service *v1.Service,
```

```
                        linkDevice string, cancel chan struct{}) (listener net.Listener) {

    maxIPAttempts := 14 // For /28 CIDR: 16 - network - broadcast

    for attempt := 0; attempt < maxIPAttempts; attempt++ {
        // 1. Allocate IP from pool
        allocatedIP, err := ipmgr.IPPoolInstance.Allocate()
        if err != nil {
            return nil
        }

        // 2. Add IP to network interface
        cidrStr := fmt.Sprintf("%s/%s", allocatedIP, ipmgr.Bits)
        managedLBIPs.AddAddr(cidrStr, linkDevice)

        // 3. Try to bind
        address := fmt.Sprintf("%s:%s", allocatedIP, port)
        listener, err = net.Listen("tcp", address)

        if err == nil {
            // Success!
            Service.Spec.LoadBalancerIP = allocatedIP
            return listener
        }

        // 4. Handle "address already in use"
        if isAddressInUse(err) {
            ipmgr.IPPoolInstance.Release(allocatedIP)
            managedLBIPs.RemoveAddr(cidrStr, linkDevice)
            continue // Try next IP
        }

        // Other errors are fatal
        return nil
    }

    return nil // Exhausted all IPs
}
```

4 IP Pool Implementation

4.1 IP Lifecycle State Diagram



4.2 Data Structure

```
type IPPool struct {
    cidr      *net.IPNet           // CIDR range (e.g., 192.168.0.224/28)
```

```
    allocated map[string]bool      // Tracks allocated IPs
    mu        sync.Mutex            // Thread-safe access
}
```

4.3 Allocation Algorithm

The allocation algorithm iterates through all IPs in the CIDR range, skipping:

- Network address (first IP)
- Broadcast address (last IP)
- Already allocated IPs

```
func (p *IPPool) Allocate() (string, error) {
    p.mu.Lock()
    defer p.mu.Unlock()

    // Iterate through CIDR range
    for ip := p.cidr.IP.Mask(p.cidr.Mask); p.cidr.Contains(ip); incIP(ip) {
        ipStr := ip.String()

        // Skip network and broadcast
        if p.isNetworkOrBroadcast(ip) {
            continue
        }

        // Check if available
        if !p.allocated[ipStr] {
            p.allocated[ipStr] = true
            return ipStr, nil
        }
    }

    return "", fmt.Errorf("no available IPs in pool")
}
```

4.4 Release Mechanism

When a service is deleted or its listener closes, the IP is released back to the pool in `mgr/listener.go:384-395`:

```
// Release the allocated IP back to the pool before closing
if ml.Service != nil && ml.Service.Spec.LoadBalancerIP != "" {
    ip := ml.Service.Spec.LoadBalancerIP

    // Only release if it's not the default CIDR base IP
    if ipmgr.DefaultCIDR != nil && ip != ipmgr.DefaultCIDR.IP {
        if ipmgr.IPPoolInstance != nil {
            ipmgr.IPPoolInstance.Release(ip)
            log.Printf("Released IP %s back to pool for service %s", ip, ml.Key)
        }
    }
}
```

5 Error Detection

5.1 Address Already In Use Detection

The `isAddressInUse` function detects bind failures due to port/IP conflicts:

```
func isAddressInUse(err error) bool {
    if err == nil {
        return false
    }

    // Check for syscall.EADDRINUSE
    if opErr, ok := err.(*net.OpError); ok {
        if osErr, ok := opErr.Err.(*syscall.Errno); ok {
            return *osErr == syscall.EADDRINUSE
        }
        return strings.Contains(opErr.Error(), "address already in use")
    }

    return strings.Contains(err.Error(), "address already in use")
}
```

6 CIDR Range Calculation

6.1 Example: /28 CIDR (192.168.0.224/28)

Purpose	Address	Notes
Network Address	192.168.0.224	Skipped (not allocated)
Usable IP 1	192.168.0.225	First allocatable IP
Usable IP 2	192.168.0.226	Second allocatable IP
…	…	…
Usable IP 14	192.168.0.238	Last allocatable IP
Broadcast	192.168.0.239	Skipped (not allocated)
Total IPs	16	
Usable IPs	14	Available for allocation

6.2 Supported CIDR Sizes

The implementation supports any valid IPv4 CIDR range:

`/28` 14 usable IPs (common for small deployments)

`/27` 30 usable IPs

`/26` 62 usable IPs

`/24` 254 usable IPs (typical class C network)

7 Network Integration

7.1 How Host Connects to k3d Pods

The load balancer running on the host can connect to k3d pod ClusterIPs through Docker's bridge network:

```
Host Network Stack
    br-2b0c6c745dc4 (172.21.0.1/16) ← Docker bridge for k3d-db
        k3d-db-server-0 (172.21.0.2) ← k3d container
            cni0 (10.42.0.1/24) ← CNI bridge inside container
                Pod IPs (10.42.0.x, 10.43.x.x ClusterIPs)

    enx803f5df6e873 (192.168.0.x) ← External interface
        192.168.0.225-238 ← LoadBalancer ExternalIPs
```

7.2 Routing Configuration

k3d automatically sets up host routes to enable pod connectivity:

```
# View routes to k3d networks
ip route | grep -E "172.21|10.43"

# Example output:
# 10.43.0.0/16 via 172.21.0.2 dev br-2b0c6c745dc4
# 172.21.0.0/16 dev br-2b0c6c745dc4 proto kernel scope link src 172.21.0.1
```

7.3 Connection Path

```
External Client
  ↓ TCP to 192.168.0.225:80 (ExternalIP on host interface)
LoadBalancer (listens on host with --network=host)
  ↓ Round-robin selects backend pod
  ↓ TCP Dial to 10.43.146.204:80 (pod ClusterIP)
Host Kernel
  ↓ Routes via 172.21.0.2 (k3d container)
k3d Container
  ↓ Routes to pod via CNI
Backend Pod
```

8 TCP Proxying

8.1 Bidirectional Pipe Implementation

The load balancer uses a bidirectional pipe pattern in `pipe/pipe.go:58-78` to forward traffic between client and backend:

```
func (pipe *Pipe) Connect() {
    done := make(chan bool, 2)

    // Client → Backend
    go func() {
        defer pipe.Close()
        io.Copy(pipe.SinkConn, pipe.SourceConn)
        done <- true
    }()

    // Backend → Client
    go func() {
        defer pipe.Close()
        io.Copy(pipe.SourceConn, pipe.SinkConn)
        done <- true
    }()
}
```

This creates a transparent TCP proxy that:

- Copies bytes in both directions simultaneously
- Doesn't parse or modify HTTP/TCP content
- Handles connection cleanup automatically

9 Configuration

9.1 Command Line Options

```
# Run with specific CIDR range
bin/loadbalancer \
```

```
    --kubeconfig=/etc/kubernetes/config.k3d \
    --restricted-cidr=192.168.0.224/28 \
    --link-device=enx803f5df6e873 \
    --debug=true
```

9.2 Docker Container Execution

```
docker run --name loadbalancer \
    --cap-add=NET_ADMIN \
    --cap-add=NET_RAW \
    --cap-add=NET_BIND_SERVICE \
    --network=host \
    -e KUBERNETES=true \
    -v $HOME/.kube/config.k3d:/etc/kubernetes/config.k3d \
    -e KUBECONFIG=/etc/kubernetes/config.k3d \
    -e DEBUG=true \
    -e LINKDEVICE=enx803f5df6e873 \
    -e RESTRICTED_CIDR=192.168.0.224/28 \
    kdc2:5000/loadbalancer:latest
```

9.3 Required Capabilities

The load balancer requires these Linux capabilities to manage network interfaces:

`CAP_NET_ADMIN` Add/remove IP addresses on interfaces

`CAP_NET_RAW` Raw socket operations

`CAP_NET_BIND_SERVICE` Bind to privileged ports (<1024)

Set via `make setcap`:

```
sudo setcap 'cap_net_admin,cap_net_raw,cap_net_bind_service=+ep' bin/loadbalancer
```

10 Operational Behavior

10.1 Service Creation Example

```
2025/10/01 19:18:49 Initialized IP pool for CIDR: 192.168.0.224/28
2025/10/01 19:18:49 ServiceWatcher Event default/sample-service for type ADD
2025/10/01 19:18:49 Service default/sample-service listener create start
2025/10/01 19:18:49 Service default/sample-service Attempting to bind to 192.168.0.225:80 (attempt 1/14)
2025/10/01 19:18:49 Service default/sample-service Address 192.168.0.225:80 already in use, trying next IP
2025/10/01 19:18:49 Service default/sample-service Attempting to bind to 192.168.0.226:80 (attempt 2/14)
2025/10/01 19:18:49 Service default/sample-service Successfully bound to 192.168.0.226:80
2025/10/01 19:18:49 SetExternalIP [192.168.0.226]
2025/10/01 19:18:49 Service default/sample-service listener created 192.168.0.226:80
```

10.2 Service Deletion Example

```
2025/10/01 19:20:15 Shutting down listener for default/sample-service
2025/10/01 19:20:15 Released IP 192.168.0.226 back to pool for service default/sample-service
2025/10/01 19:20:15 Removing ExternalIP [192.168.0.226]
2025/10/01 19:20:15 RemoveAddr 192.168.0.226/28 enx803f5df6e873
```

11 Testing

11.1 Manual Testing Steps

1. Start the load balancer:

```
bin/loadbalancer --kubeconfig=$HOME/.kube/config.k3d --debug=true
```

2. Create a test service in k3d:

```
kubectl apply -f - <<EOF
apiVersion: v1
kind: Service
metadata:
  name: test-service-1
spec:
  type: LoadBalancer
  ports:
  - port: 80
    targetPort: 8080
  selector:
    app: test
EOF
```

3. Verify IP allocation:

```
# Check assigned external IP
kubectl get svc test-service-1 -o jsonpath='{.spec.externalIPs[0]}'

# Verify IP is on network interface
ip addr show enx803f5df6e873 | grep 192.168.0
```

4. Create a second service to test IP allocation:

```
kubectl apply -f - <<EOF
apiVersion: v1
kind: Service
metadata:
  name: test-service-2
spec:
  type: LoadBalancer
  ports:
  - port: 80
    targetPort: 8080
  selector:
    app: test
EOF
```

5. Verify both services have different IPs:

```
kubectl get svc -o wide | grep test-service
```

11.2 Expected Results

- First service gets `192.168.0.225` (or next available)
- Second service gets `192.168.0.226` (next in sequence)
- Deleting first service releases `192.168.0.225` back to pool
- Creating third service reuses `192.168.0.225`

12 Troubleshooting

12.1 IP Pool Exhaustion

If all IPs in the CIDR are allocated:

`ERROR: Failed to allocate IP from pool: no available IPs in pool`

Solution: Increase CIDR size or delete unused services.

12.2 Address Already In Use (All IPs)

If all attempts fail:

```
ERROR: Service default/test-service Exhausted all IP allocation attempts
```

Possible Causes:

- External process using IPs in the range
- Another load balancer instance running
- Stale IPs from previous crashes

Solution:

```
# Check what's listening on the IPs
for ip in {225..238}; do
    sudo ss -tlnp | grep "192.168.0.$ip:80"
done

# Manually release stuck IPs
sudo ip addr del 192.168.0.225/28 dev enx803f5df6e873
```

12.3 Network Interface Not Found

```
ERROR: Auto-detected interface 'enx803f5df6e873' also has no IPv4 addresses
```

Solution: Verify interface exists and has IP:

```
ip addr show enx803f5df6e873
```

13 Future Enhancements

13.1 Potential Improvements

1. **Persistent IP Allocation**
   - Store IP allocations in Kubernetes annotations
   - Survive load balancer restarts with same IP assignments
2. **IP Affinity**
   - Prefer same IP when service is recreated
   - Use service name hash for deterministic allocation
3. **Multi-CIDR Support**
   - Support multiple CIDR ranges
   - Automatic failover to secondary CIDR when primary exhausted
4. **Health-Based Deallocation**
   - Detect and release IPs from services with no healthy endpoints
   - Automatic cleanup of orphaned IPs
5. **Metrics and Monitoring**
   - Expose IP pool utilization metrics
   - Alert when pool usage exceeds threshold

14 References

14.1 Source Files

- ipmgr/cidr.go:154 - IPPool implementation
- mgr/open.go:83 - ListenWithIPAllocation function
- mgr/ipmgrinit.go:105 - IP pool initialization
- mgr/listener.go:384 - IP cleanup on close

14.2 Related Documentation

- Docker Registry Setup
- Project README

15 Copyright

Copyright 2018-2025 David Walter.
Licensed under the Apache License, Version 2.0.