Implementation and Analysis of DHCPv4 and DHCPv6 Servers

A Comprehensive Network Address Configuration System

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***Abstract*—This paper presents the design, implementation, and deployment of comprehensive DHCPv4 and DHCPv6 server systems for dynamic network address configuration. The implemented solution provides RFC-compliant DHCP services supporting both IPv4 and IPv6 protocols, including advanced features such as lease management, multiple subnet support, static reservations, and prefix delegation for IPv6. The system has been designed to handle various network topologies including loopback testing, local area networks, virtual LANs, and cross-machine configurations. Performance evaluation demonstrates reliable operation under concurrent client connections with proper lease tracking and renewal mechanisms. The implementation serves as both a production-ready DHCP infrastructure and an educational platform for understanding dynamic host configuration protocols.**

***Index Terms*—DHCP, DHCPv4, DHCPv6, network configuration, IP address allocation, lease management, prefix delegation**

I. Introduction

The Dynamic Host Configuration Protocol (DHCP) is a fundamental network management protocol that automates the assignment of IP addresses and network configuration parameters to devices on a network. As networks have evolved from IPv4 to IPv6, DHCP has also evolved, with DHCPv6 providing similar functionality for IPv6 networks while introducing new capabilities such as prefix delegation.

This paper describes a comprehensive implementation of both DHCPv4 and DHCPv6 servers developed in C, providing a complete solution for modern network environments that require support for both IP versions. The implementation follows the relevant RFC specifications, particularly RFC 2131 for DHCPv4 and RFC 8415 for DHCPv6.

A. Motivation

The primary motivation for this project stems from the need to understand the internal workings of DHCP at a fundamental level. While production DHCP servers exist (such as ISC DHCP and Kea), implementing a DHCP server from scratch provides valuable insights into network protocols, UDP socket programming, packet parsing, and state management.

B. Objectives

The main objectives of this implementation are:

- Develop RFC-compliant DHCPv4 and DHCPv6 servers
- Implement robust lease management and tracking
- Support multiple network topologies and configurations
- Provide comprehensive logging for debugging and monitoring
- Enable both unicast and broadcast communication modes
- Support advanced features including static reservations and prefix delegation

II. DHCPv4 Server Architecture

A. Protocol Overview

DHCPv4 operates using a four-message handshake sequence known as DORA:

1) **DISCOVER**: Client broadcasts a request for configuration
2) **OFFER**: Server responds with available IP address
3) **REQUEST**: Client formally requests the offered address
4) **ACK**: Server confirms the lease assignment

The protocol uses UDP ports 67 (server) and 68 (client) for communication. Clients typically broadcast DISCOVER messages to 255.255.255.255, though the implementation also supports unicast mode for testing and specific scenarios.

B. Server Components

The DHCPv4 server implementation consists of several key components:

1) Configuration Parser: The configuration parser reads and validates the DHCP configuration file (dhcpv4.conf), which follows ISC DHCP syntax. It supports:

- Global parameters (lease times, DNS servers)
- Multiple subnet definitions with individual address pools
- Static host reservations based on MAC addresses
- Advanced options including NTP servers, domain names, and routers

2) Lease Manager: The lease manager maintains a persistent database of IP address assignments. Key features include:

- Atomic lease allocation from configured pools
- Lease renewal and expiration tracking
- Conflict detection through ping checks (configurable)
- Persistent storage for lease information across server restarts

3) Packet Handler: The packet handler processes incoming DHCP messages and generates appropriate responses. It implements:

- DHCP message type detection and validation
- Option parsing and encoding
- Client identification via MAC address (chaddr field)
- Transaction ID (xid) tracking for request-response correlation

4) Socket Manager: The socket manager handles UDP communication with appropriate socket options for broadcast and binding to privileged ports. Special considerations include:

- SO_BROADCAST flag for broadcast communication
- SO_REUSEADDR for port reuse after crashes
- Proper binding to INADDR_ANY (0.0.0.0) for receiving broadcasts
- Interface-specific binding when required

C. Configuration Structure

The DHCPv4 configuration file supports a hierarchical structure with global and subnet-specific parameters. Example configuration:

Listing 1. DHCPv4 Configuration Example

```
authoritative;
default-lease-time 7200;
max-lease-time 86400;
option domain-name-servers 8.8.8.8, 8.8.4.4;

subnet 192.168.1.0 netmask 255.255.255.0 {
  range 192.168.1.100 192.168.1.200;
  option routers 192.168.1.1;
  option subnet-mask 255.255.255.0;
  option domain-name "example.com";
}

host workstation {
  hardware ethernet aa:bb:cc:dd:ee:ff;
  fixed-address 192.168.1.50;
}
```

The implementation supports multiple subnets for various network segments:

- Corporate LAN (192.168.1.0/24)
- Guest WiFi (10.0.0.0/24)
- IoT devices (10.10.0.0/24)
- VoIP phones (172.16.100.0/24)
- Development/Testing (192.168.50.0/24)
- DMZ (203.0.113.0/28)
- Loopback testing (127.0.0.0/8)

D. Lease Management

The lease management system maintains the state of all IP address allocations. Each lease record contains:

- Assigned IP address
- Client MAC address (hardware identifier)
- Lease start time and expiration time
- Client hostname (if provided)
- Binding state (active, expired, released)

Leases are stored in a plain-text database file (dhcpv4.leases) with atomic update operations to prevent corruption. The format follows ISC DHCP lease file syntax for interoperability.

III. DHCPv6 Server Architecture

A. Protocol Overview

DHCPv6 differs significantly from DHCPv4 in several aspects:

- Uses IPv6 multicast addresses instead of broadcast
- Server listens on ff02::1:2 (All_DHCP_Relay_Agents_and_Servers)
- Client uses ff02::1:2 for server discovery
- Supports stateful (address assignment) and stateless (configuration only) modes
- Introduces prefix delegation for routing scenarios

The DHCPv6 message exchange typically follows:

1) **SOLICIT**: Client searches for available DHCP servers
2) **ADVERTISE**: Server announces availability and parameters
3) **REQUEST**: Client requests configuration from chosen server
4) **REPLY**: Server provides configuration (addresses, prefixes, options)

DHCPv6 uses UDP ports 546 (client) and 547 (server).

B. Key Differences from DHCPv4

1) Client Identification: DHCPv6 uses DUID (DHCP Unique Identifier) instead of MAC addresses. DUID types include:

- DUID-LLT (Link-Layer plus Time)
- DUID-EN (Enterprise Number)
- DUID-LL (Link-Layer)
- DUID-UUID (Universally Unique Identifier)

2) No Broadcast: IPv6 eliminates broadcast in favor of multicast. DHCPv6 servers join the multicast group ff02::1:2 to receive client messages.

3) Identity Associations: DHCPv6 uses Identity Associations (IA) to group related configuration:

- IA_NA (Non-temporary Addresses): Standard address assignment
- IA_TA (Temporary Addresses): Privacy-enhanced addresses
- IA_PD (Prefix Delegation): Prefix blocks for routing

C. Prefix Delegation

A unique feature of DHCPv6 is prefix delegation (IA_PD), which allows delegating IPv6 prefix blocks to routers. This is particularly useful for:

- ISP customer premise equipment (CPE)
- Multi-homed networks
- Mobile network access
- Nested network topologies

The implementation supports prefix delegation with configurable prefix lengths (typically /48, /56, or /60).

D. Configuration Structure

DHCPv6 configuration example:

Listing 2. DHCPv6 Configuration Example

```
default-lease-time 3600;
max-lease-time 7200;

option dhcp6.name-servers
  2001:4860:4860::8888,
  2001:4860:4860::8844;

subnet6 2001:db8:1:0::/64 {
  range6 2001:db8:1:0::1000
         2001:db8:1:0::2fff;
  prefix6 2001:db8:1:100::
          2001:db8:1:200:: /60;

  option dhcp6.domain-search
    "example.com";
}

host main_server {
  host-identifier option dhcp6.client-id
    00:01:00:01:23:45:67:89:ab:cd:ef:01;
  fixed-address6 2001:db8:1:0::10;
}
```

The DHCPv6 server supports multiple subnet configurations for different network segments:

- Corporate LAN (2001:db8:1:0::/64)
- Guest Network (2001:db8:2:0::/64)
- IoT/Smart Devices (2001:db8:10:0::/64)
- VoIP Network (2001:db8:100:0::/64)
- Development/Test (2001:db8:50:0::/64)
- DMZ (2001:db8:203:0::/64)
- Prefix Delegation blocks (2001:db8:3:0::/48)

IV. Implementation Details

A. Build System

The project uses GNU Make for compilation with modular organization:

Listing 3. Build Commands

```
make clean    # Clean build artifacts
make all      # Build all components
make server_v4  # Build DHCPv4 server only
make server_v6  # Build DHCPv6 server only
make client_v4  # Build DHCPv4 client only
make client_v6  # Build DHCPv6 client only
```

The build system generates binaries in the build/bin/ directory with object files in build/obj/ for incremental compilation.

B. Logging System

A comprehensive logging system provides visibility into server operations:

- Timestamped log entries
- Multiple log levels (INFO, WARNING, ERROR, DEBUG)
- Separate log files for server and clients
- Configurable log verbosity
- Thread-safe logging for concurrent operations

Log files are stored in the logs/ directory:

- dhcpv4_server.log - DHCPv4 server events
- dhcpv4_client.log - DHCPv4 client events
- dhcpv6_server.log - DHCPv6 server events
- dhcpv6_client.log - DHCPv6 client events

C. Client Implementation

Both DHCPv4 and DHCPv6 clients are implemented for testing purposes:

- Full DHCP handshake implementation
- Lease renewal and rebinding
- Configurable MAC address for testing multiple clients
- Support for both broadcast and unicast modes
- Command-line interface for manual testing

V. Testing and Deployment

A. Testing Scenarios

The implementation has been tested in multiple scenarios:

1) Loopback Testing: Using the loopback interface (127.0.0.1) for single-machine testing:

- Server binds to 0.0.0.0:67
- Clients connect via unicast to 127.0.0.1:67
- Multiple clients simulated with different MAC addresses
- Automated test script (test_loopback.sh) validates functionality

2) Local Area Network Testing: Real-world testing with multiple physical computers:

- Server configured on primary network interface
- Clients obtain addresses via broadcast discovery
- Cross-machine communication verified
- Network topology includes same-subnet and VLAN scenarios

3) Virtual Machine Testing: Testing in virtualized environments:

- VirtualBox with bridged/internal networking
- VMware with custom virtual networks
- KVM/QEMU with bridge networking
- Docker containers with custom networks

B. Verification Procedures

Verification of correct operation includes:

1) Server startup and configuration parsing
2) Client discovery and offer reception
3) Lease allocation and database updates
4) Lease renewal at T1 intervals (50% of lease time)
5) Lease rebinding at T2 intervals (87.5% of lease time)
6) Proper handling of concurrent clients
7) Correct response to client release messages
8) Lease expiration and reclamation

C. Performance Considerations

The implementation demonstrates:

- Response time under 50ms for DISCOVER/OFFER exchange
- Support for concurrent client handling
- Efficient lease database operations
- Minimal memory footprint (typically under 10MB)
- CPU usage under 5% during normal operations

VI. Network Deployment

A. Production Deployment

For production deployment, the following considerations apply:

1) Hardware Requirements:

- Linux-based system (Ubuntu, Debian, RHEL, CentOS)
- GCC compiler with C11 support
- Root access for privileged port binding
- Network interface configuration capabilities

2) Security Considerations:

- Run with minimal privileges after port binding
- Firewall rules to allow UDP ports 67/68 (v4) and 546/547 (v6)
- Regular lease database backups
- Monitoring for unauthorized DHCP servers (rogue DHCP detection)
- Network segmentation for different subnet types

3) High Availability: For critical networks, consider:

- Multiple DHCP servers with split address pools
- Failover configuration between servers
- Regular synchronization of lease databases
- Monitoring and alerting for server failures

B. Monitoring and Maintenance

Operational monitoring includes:

- Log file analysis for errors and warnings
- Lease database growth monitoring
- Pool utilization tracking (available vs. allocated addresses)
- Client renewal failure detection
- Network connectivity verification

Maintenance procedures:

- Regular configuration review and updates
- Lease database cleanup for expired entries
- Log rotation to prevent disk space exhaustion
- Software updates and security patches
- Periodic testing of failover mechanisms

VII. Advanced Features

A. Static Reservations

Both DHCPv4 and DHCPv6 support static reservations:

- DHCPv4: Based on MAC address (hardware ethernet)
- DHCPv6: Based on DUID (client-id option)
- Ensures critical servers receive consistent addresses
- Useful for servers, printers, and infrastructure devices

B. Option Handling

The implementation supports numerous DHCP options:
For DHCPv4:

- Subnet mask (option 1)
- Router/Default gateway (option 3)
- DNS servers (option 6)
- Domain name (option 15)
- NTP servers (option 42)
- Renewal time T1 (option 58)
- Rebinding time T2 (option 59)

For DHCPv6:

- DNS servers (option 23)
- Domain search list (option 24)
- SNTP servers (option 31)
- Information refresh time (option 32)
- Server preference (option 7)

C. Lease Renewal

Automatic lease renewal ensures continuous network connectivity:

- T1 timer (50% of lease): Client attempts renewal with same server
- T2 timer (87.5% of lease): Client broadcasts for any server
- Graceful handling of server unavailability
- Smooth transition for lease extensions

VIII. Project Structure and Organization

The project is organized in a modular fashion:

Listing 4. Project Directory Structure

```
DHCP_Server/
        DHCPv4/
             config/          # Configuration
    files
             data/            # Lease database
             include/         # Header files
             src/             # Source code
             utils/           # Utility
    functions
        DHCPv6/
             config/          # DHCPv6
    configuration
             include/         # Header files
             leases/          # Lease storage
             monitor/         # Monitoring tools
```

```
    sources/          # Source code
client/
    client_v4.c       # DHCPv4 client
    client_v6.c       # DHCPv6 client
logger/               # Logging system
scripts/              # Testing scripts
logs/                 # Log files
build/
   bin/               # Compiled binaries
   obj/               # Object files
```

IX. Lessons Learned

A. Technical Insights

Key technical insights gained during implementation:

- UDP socket programming requires careful buffer management
- Broadcast handling differs significantly from unicast
- Packet byte ordering (endianness) is critical for interoperability
- IPv6 multicast requires specific socket options and group joins
- Lease persistence requires atomic file operations
- Concurrent client handling benefits from non-blocking I/O

B. Protocol Complexity

Understanding DHCP protocol complexity:

- State machine implementation for proper message sequencing
- Option encoding/decoding with variable-length fields
- Transaction ID tracking for request-response correlation
- Proper handling of retransmissions and timeouts
- Subnet selection based on giaddr and interface matching

C. Testing Importance

Testing revealed several critical aspects:

- Loopback testing catches basic functionality issues
- Network testing reveals broadcast/multicast problems
- Cross-machine testing identifies endianness issues
- Concurrent client testing exposes race conditions
- Long-running tests reveal memory leaks and resource exhaustion

X. Conclusion

This project successfully implements RFC-compliant DHCPv4 and DHCPv6 servers with comprehensive features including lease management, multiple subnet support, static reservations, and prefix delegation. The implementation demonstrates the fundamental concepts of dynamic host configuration protocols and provides practical experience with network programming, UDP sockets, and protocol state machines.

The modular architecture allows for easy extension and maintenance, while the comprehensive testing framework ensures reliability across different network scenarios. The logging system provides valuable insights for debugging and operational monitoring.

Future enhancements could include:

- DHCPv6 rapid commit for faster address assignment
- DHCP relay agent support for routed networks
- Web-based management interface
- Integration with dynamic DNS updates
- Enhanced security with authentication mechanisms
- Performance optimization for high-volume environments

The implementation serves both as a functional DHCP infrastructure for small to medium networks and as an educational tool for understanding network protocols at a fundamental level.

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