路由器转发实验

2024年12月1日

2024E8013282087-陈潇

实验内容

在主机上安装arptables, iptables，用于禁止每个节点的相应功能

```
sudo apt install arptables iptables
```

运行给定网络拓扑(router_topo.py) 在r1上执行路由器程序**在h1上进行ping实验**

- 设计思路 在已有代码框架的基础上完成 `arp.c`，实现ARP包的回复和请求，以及对ARP包的处理。
  - 实现 `create_arp_packet(iface_info_t *iface, u32 dst_ip, struct ether_arp *req_hdr, int is_reply)` 函数描述：为了减少代码的重复，我将 `ARP`请求和 `ARP`响应的包构建逻辑提取到了一个名为 `create_arp_packet` 的辅助函数中。这样，无论是发送 `ARP`请求还是回复，都能通过调用该函数来生成 `ARP`包，避免了冗余的代码。 代码实现：

```
// Utility function to create an ARP packet
static char* create_arp_packet(iface_info_t *iface, u32 dst_ip, struct
ether_arp *req_hdr, int is_reply)
{
    char *packet = (char *)malloc(sizeof(struct ether_header) +
sizeof(struct ether_arp));
    struct ether_header *header = (struct ether_header *)packet;
    struct ether_arp *arp = (struct ether_arp *)(packet + sizeof(struct
ether_header));

    // Fill ether_header
    header->ether_type = htons(ETH_P_ARP);
    memcpy(header->ether_shost, iface->mac, ETH_ALEN);
```

```
    if (is_reply) {
        memcpy(header->ether_dhost, req_hdr->arp_sha, ETH_ALEN); // For
ARP reply, set destination MAC to source MAC of request
    } else {
        memset(header->ether_dhost, 0xff, ETH_ALEN); // For ARP
request, broadcast
    }

    // Fill arp header
    arp->arp_hrd = htons(ARPHRD_ETHER);
    arp->arp_pro = htons(0x0800);
    arp->arp_hln = 6;
    arp->arp_pln = 4;
    arp->arp_op = htons(is_reply ? ARPOP_REPLY : ARPOP_REQUEST);

    memcpy(arp->arp_sha, iface->mac, ETH_ALEN);
    memset(arp->arp_tha, 0, ETH_ALEN); // Target hardware address is
zero in requests
    arp->arp_spa = htonl(iface->ip);
    arp->arp_tpa = htonl(dst_ip);

    return packet;
}
```

- `arp_send_request(iface_info_t *iface, u32 dst_ip)` 函数描述：发送 ARP响应，目标是广播地址。代码实现：

```
void arp_send_request(iface_info_t *iface, u32 dst_ip)
{
    char *packet = create_arp_packet(iface, dst_ip, NULL, 0);  // 传递0
表示请求
    iface_send_packet(iface, packet, sizeof(struct ether_header) +
sizeof(struct ether_arp));
}
```

- `arp_send_reply(iface_info_t *iface, struct ether_arp *req_hdr)` 函数描述：发送 ARP响应，目标是 ARP请求中的源 MAC。代码实现：

```
void arp_send_reply(iface_info_t *iface, struct ether_arp *req_hdr)
{
    char *packet = create_arp_packet(iface, ntohl(req_hdr->arp_spa),
req_hdr, 1);  // 传递1表示回复
    iface_send_packet(iface, packet, sizeof(struct ether_header) +
sizeof(struct ether_arp));
}
```

- `handle_arp_packet(iface_info_t *iface, char *packet, int len)` 函数描述：处理接收到的 ARP包。根据 ARP包中的操作类型 (`arp_op`)，判断是请求还是回复，并作出相应的处理：
  - ARP请求：如果目标 IP是本机 IP，则发送 ARP回复，并将请求中的源 IP和源 MAC插入到 ARP缓存中。
  - ARP回复：将源 IP和源 MAC插入到 ARP缓存中。 代码实现：

```
void handle_arp_packet(iface_info_t *iface, char *packet, int len)
{
    struct ether_arp *arp = (struct ether_arp *)(packet + sizeof(struct
ether_header));

    switch (ntohs(arp->arp_op)) {
        case ARPOP_REQUEST:
            if (ntohl(arp->arp_tpa) == iface->ip) {
                arp_send_reply(iface, arp);
            }
            arpcache_insert(htonl(arp->arp_spa), arp->arp_sha);
            break;
        case ARPOP_REPLY:
            arpcache_insert(htonl(arp->arp_spa), arp->arp_sha);
            break;
        default:
            free(packet);
            break;
    }
}
```

- `iface_send_packet_by_arp(iface_info_t *iface, u32 dst_ip, char *packet, int len)` 函数描述：该函数通过查找 ARP缓存来发送 IP包。如果目标 IP的 MAC地址已经缓存，则直接将目标 MAC填入以太网头并发送；否则，先将 IP包挂起，并发送 ARP请求以查询目标 MAC。 代码实现：

```
void iface_send_packet_by_arp(iface_info_t *iface, u32 dst_ip, char
*packet, int len)
{
    struct ether_header *eh = (struct ether_header *)packet;
    memcpy(eh->ether_shost, iface->mac, ETH_ALEN);
    eh->ether_type = htons(ETH_P_IP);

    u8 dst_mac[ETH_ALEN];
    int found = arpcache_lookup(dst_ip, dst_mac);

    if (found) {
        memcpy(eh->ether_dhost, dst_mac, ETH_ALEN);
        iface_send_packet(iface, packet, len);
```

```
    } else {
        arpcache_append_packet(iface, dst_ip, packet, len);
    }
}
```

在已有代码框架的基础上完成 `arpcache.c`，实现ARP缓存相关操作

- 实现 `int arpcache_lookup(u32 ip4, u8 mac[ETH_ALEN])` 函数描述：查询 `ARP`缓存，如果查到就返回 `1`，没查到返回 `0`。 代码实现：

```
// lookup the IP->mac mapping
int arpcache_lookup(u32 ip4, u8 mac[ETH_ALEN])
{
    pthread_mutex_lock(&arpcache.lock);
    for (int i = 0; i < MAX_ARP_SIZE; i++) {
        if (arpcache.entries[i].ip4 == ip4 &&
arpcache.entries[i].valid) {
            memcpy(mac, arpcache.entries[i].mac, ETH_ALEN);
            pthread_mutex_unlock(&arpcache.lock);
            return 1;
        }
    }
    pthread_mutex_unlock(&arpcache.lock);
    return 0;
}
```

- `void arpcache_append_packet(iface_info_t *iface, u32 ip4, char *packet, int len)` 函数描述：将要发送的数据包添加到待发送数据包队列中。 代码实现：

```
// append the packet to arpcache
void arpcache_append_packet(iface_info_t *iface, u32 ip4, char *packet,
int len)
{
    pthread_mutex_lock(&arpcache.lock);
    int uncached = 1;
    struct arp_req *entry, *q;
    struct cached_pkt *pkt = (struct cached_pkt *)malloc(sizeof(struct
cached_pkt));
    pkt->len = len;
    pkt->packet = packet;
    init_list_head(&pkt->list);

    // Search for an existing entry in the request list
    list_for_each_entry_safe(entry, q, &arpcache.req_list, list)
    {
        if (entry->ip4 == ip4) {
            list_add_tail(&pkt->list, &(entry->cached_packets));
```

```
                uncached = 0;
                break;
            }
        }

    if (uncached == 1) {
        // Create a new request entry if not found
        struct arp_req *new_req = (struct arp_req
*)malloc(sizeof(struct arp_req));
        init_list_head(&new_req->list);
        new_req->iface = iface;
        new_req->ip4 = ip4;
        new_req->sent = time(NULL);
        new_req->retries = 0;
        init_list_head(&new_req->cached_packets);
        list_add_tail(&new_req->list, &arpcache.req_list);
        list_add_tail(&pkt->list, &new_req->cached_packets);
        arp_send_request(iface, ip4);
    }

    pthread_mutex_unlock(&arpcache.lock);
}
```

- `void arpcache_insert(u32 ip4, u8 mac[ETH_ALEN])` 函数描述: 将新的对应关系插入缓存，并检查是否存在等待该关系的数据包。 代码实现:

```
void arpcache_insert(u32 ip4, u8 mac[ETH_ALEN])
{
    pthread_mutex_lock(&arpcache.lock);
    int idx = find_empty_entry(ip4);

    // If an empty entry is found, insert the new entry
    if (idx >= 0) {
        arpcache.entries[idx].ip4 = ip4;
        memcpy(arpcache.entries[idx].mac, mac, ETH_ALEN);
        arpcache.entries[idx].added = time(NULL);
        arpcache.entries[idx].valid = 1;
    } else {
        // If no empty entry is available, replace a random entry
        srand(time(NULL));
        int index = rand() % MAX_ARP_SIZE;
        arpcache.entries[index].ip4 = ip4;
        memcpy(arpcache.entries[index].mac, mac, ETH_ALEN);
        arpcache.entries[index].added = time(NULL);
        arpcache.entries[index].valid = 1;
    }

    // Process and send any pending packets
    struct arp_req *entry, *q;
    list_for_each_entry_safe(entry, q, &arpcache.req_list, list)
    {
        if (entry->ip4 == ip4) {
```

```
            struct cached_pkt *pkt_entry, *pkt;
            list_for_each_entry_safe(pkt_entry, pkt, &entry->cached_packets, list)
            {
                struct ether_header *eh = (struct ether_header *)(pkt_entry->packet);
                memcpy(eh->ether_shost, entry->iface->mac, ETH_ALEN);
                memcpy(eh->ether_dhost, mac, ETH_ALEN);
                eh->ether_type = htons(ETH_P_IP);
                iface_send_packet(entry->iface, pkt_entry->packet, pkt_entry->len);
                list_delete_entry(&pkt_entry->list);
                free(pkt_entry);
            }
            list_delete_entry(&entry->list);
            free(entry);
        }
    }

    pthread_mutex_unlock(&arpcache.lock);
}
```

- `void *arpcache_sweep(void *arg)` 函数描述：`arpcache_sweep` 函数每秒循环执行，首先通过互斥锁访问 ARP缓存，清理掉超过 15秒未更新的过期条目。然后，它遍历 ARP请求列表，对于超时超过 1秒且重试次数不超过 5次的请求，重新发送 ARP请求；如果重试次数超过最大限制，则将相关缓存包移至临时列表，并删除该请求。最后，函数遍历临时列表，发送 ICMP不可达消息，并释放相关资源，确保 ARP请求的失败及时通知发送方。 代码实现：

```
// sweep arpcache periodically
void *arpcache_sweep(void *arg)
{
    while (1) {
        sleep(1);
        struct cached_pkt *tmp_list = (struct cached_pkt *)malloc(sizeof(struct cached_pkt));
        init_list_head(&tmp_list->list);

        pthread_mutex_lock(&arpcache.lock);

        // Remove expired entries
        for (int i = 0; i < MAX_ARP_SIZE; i++) {
            if (arpcache.entries[i].valid && (time(NULL) - arpcache.entries[i].added) > ARP_ENTRY_TIMEOUT)
                arpcache.entries[i].valid = 0;
        }

        // Process ARP requests
        struct arp_req *entry, *q;
```

```
        list_for_each_entry_safe(entry, q, &arpcache.req_list, list)
        {
            if ((time(NULL) - entry->sent) > 1 && entry->retries <= 5)
{
                entry->sent = time(NULL);
                entry->retries++;
                arp_send_request(entry->iface, entry->ip4);
            } else if (entry->retries > ARP_REQUEST_MAX_RETRIES) {
                struct cached_pkt *pkt_entry, *pkt;
                list_for_each_entry_safe(pkt_entry, pkt, &entry-
>cached_packets, list)
                {
                    struct cached_pkt *tmp = (struct cached_pkt
*)malloc(sizeof(struct cached_pkt));
                    init_list_head(&tmp->list);
                    tmp->len = pkt_entry->len;
                    tmp->packet = pkt_entry->packet;
                    list_add_tail(&tmp->list, &tmp_list->list);
                    list_delete_entry(&pkt_entry->list);
                    free(pkt_entry);
                }
                list_delete_entry(&entry->list);
                free(entry);
            }
        }

        pthread_mutex_unlock(&arpcache.lock);

        // Send ICMP unreachable messages for dropped packets
        struct cached_pkt *pkt_entry, *pkt;
        list_for_each_entry_safe(pkt_entry, pkt, &tmp_list->list, list)
        {
            icmp_send_packet(pkt_entry->packet, pkt_entry->len,
ICMP_DEST_UNREACH, ICMP_HOST_UNREACH);
            list_delete_entry(&pkt_entry->list);
            free(pkt_entry);
        }
    }

    return NULL;
}
```

- `iface_send_packet_by_arp(iface_info_t *iface, u32 dst_ip, char *packet, int len)` 函数描述：该函数通过查找 `ARP`缓存来发送 `IP`包。如果目标 `IP`的 `MAC`地址已经缓存，则直接将目标 `MAC`填入以太网头并发送；否则，先将 `IP`包挂起，并发送 `ARP`请求以查询目标 `MAC`。 代码实现：

```
void iface_send_packet_by_arp(iface_info_t *iface, u32 dst_ip, char
*packet, int len)
```

```
{
    struct ether_header *eh = (struct ether_header *)packet;
    memcpy(eh->ether_shost, iface->mac, ETH_ALEN);
    eh->ether_type = htons(ETH_P_IP);

    u8 dst_mac[ETH_ALEN];
    int found = arpcache_lookup(dst_ip, dst_mac);

    if (found) {
        memcpy(eh->ether_dhost, dst_mac, ETH_ALEN);
        iface_send_packet(iface, packet, len);
    } else {
        arpcache_append_packet(iface, dst_ip, packet, len);
    }
}
```

在已有代码框架的基础上完成 `ip_base.c`，实现 `IP`前缀查找和发送 `IP`数据包。

- 实现 `void ip_init_hdr(struct iphdr *ip, u32 saddr, u32 daddr, u16 len, u8 proto)` 函数描述：查找得到最长前缀对应的路由表项。 代码实现：

```
void ip_init_hdr(struct iphdr *ip, u32 saddr, u32 daddr, u16 len, u8
proto)
{
    ip->version = 4;
    ip->ihl = 5;
    ip->tos = 0;
    ip->tot_len = htons(len);
    ip->id = rand();
    ip->frag_off = htons(IP_DF);
    ip->ttl = DEFAULT_TTL;
    ip->protocol = proto;
    ip->saddr = htonl(saddr);
    ip->daddr = htonl(daddr);
    ip->checksum = ip_checksum(ip);
}
```

- `void ip_send_packet(char *packet, int len)` 函数描述：在发送 `ICMP`数据包时进行的 `ip`数据包发送。 代码实现：

```
void ip_send_packet(char *packet, int len)
{
    struct iphdr *header = packet_to_ip_hdr(packet);  // Extract the IP
header from the packet
    rt_entry_t *entry = longest_prefix_match(ntohl(header->daddr));  //
Find the route for the destination address
```

```
    if (!entry)
    {
        // If no matching route is found, drop the packet
        fprintf(stderr, "No route found for destination IP: %s\n", inet_ntoa(*(struct in_addr *)&header->daddr));
        free(packet);
        return;
    }

    // If the router interface is in the same network as the destination IP, send directly
    // Otherwise, send through the gateway
    u32 dst = entry->gw ? entry->gw : ntohl(header->daddr);

    // Prepare Ethernet header
    struct ether_header *eh = (struct ether_header *)(packet);
    memcpy(eh->ether_shost, entry->iface->mac, ETH_ALEN);  // Set the source MAC address
    eh->ether_type = htons(ETH_P_IP);  // Set the EtherType to IP

    // Send the packet using ARP (if gateway is required)
    iface_send_packet_by_arp(entry->iface, dst, packet, len);
}
```

在已有代码框架的基础上完成 `icmp.c`，实现 `ICMP`数据包的发送。

- 实现 `void handle_ip_packet(iface_info_t *iface, char *packet, int len)` 函数描述：如果收到的包目的是本路由器端口 ,并且 ICMP 首部 type为 请求 ,回应 ICMP 报文,否则转发。 代码实现：

```
// send icmp packet
void icmp_send_packet(const char *in_pkt, int len, u8 type, u8 code)
{
  struct ether_header *in_eh = (struct ether_header*)(in_pkt);
  struct iphdr *in_iph = packet_to_ip_hdr(in_pkt);

  int packet_len;

  if (type == ICMP_ECHOREPLY && code == ICMP_NET_UNREACH)
  {
    packet_len = len;
  }
  else
  {
    packet_len = ETHER_HDR_SIZE+IP_BASE_HDR_SIZE+ICMP_HDR_SIZE+IP_HDR_SIZE(in_iph) + 8;//需要拷贝收到数据包的IP头部（>= 20字节）和随后的8字节
  }
  char *packet = (char *)malloc(packet_len);
  struct ether_header *eh = (struct ether_header *)(packet);
  struct iphdr *iph = packet_to_ip_hdr(packet);
  struct icmphdr *icmph = (struct icmphdr *)(packet + ETHER_HDR_SIZE + IP_BASE_HDR_SIZE);
```

```
  eh->ether_type = htons(ETH_P_IP);
  memcpy(eh->ether_dhost, in_eh->ether_dhost, ETH_ALEN);
  memcpy(eh->ether_shost, in_eh->ether_dhost, ETH_ALEN);

  u32 saddr = ntohl(in_iph->saddr);
  rt_entry_t *entry = longest_prefix_match(saddr);
  ip_init_hdr(iph, entry->iface->ip,saddr, packet_len-ETHER_HDR_SIZE,
1);

  icmph->type = type;
  icmph->code = code;

  char *rest_1 = (char *)((char *)in_iph + IP_HDR_SIZE(in_iph) +
ICMP_HDR_SIZE - 4);
  char *rest_2 = (char *)((char *)icmph + ICMP_HDR_SIZE - 4);


  if (type == ICMP_ECHOREPLY && code == ICMP_NET_UNREACH)
  {
    memcpy(rest_2, rest_1, len - ETHER_HDR_SIZE - IP_HDR_SIZE(in_iph) -
ICMP_HDR_SIZE + 4);
    icmph->checksum = icmp_checksum(icmph, packet_len - ETHER_HDR_SIZE
- IP_HDR_SIZE(in_iph));
  }
  else
  {
    memset(rest_2, 0, 4);
    memcpy(rest_2 + 4, in_iph, IP_HDR_SIZE(in_iph) + 8);和随后的8字节
    icmph->checksum = icmp_checksum(icmph, IP_HDR_SIZE(in_iph) + 8 +
ICMP_HDR_SIZE);
  }
  ip_send_packet(packet, packet_len);
}
```

- 实验结果
  - 先make生成对应的可执行文件：此时会报很多 `warning`

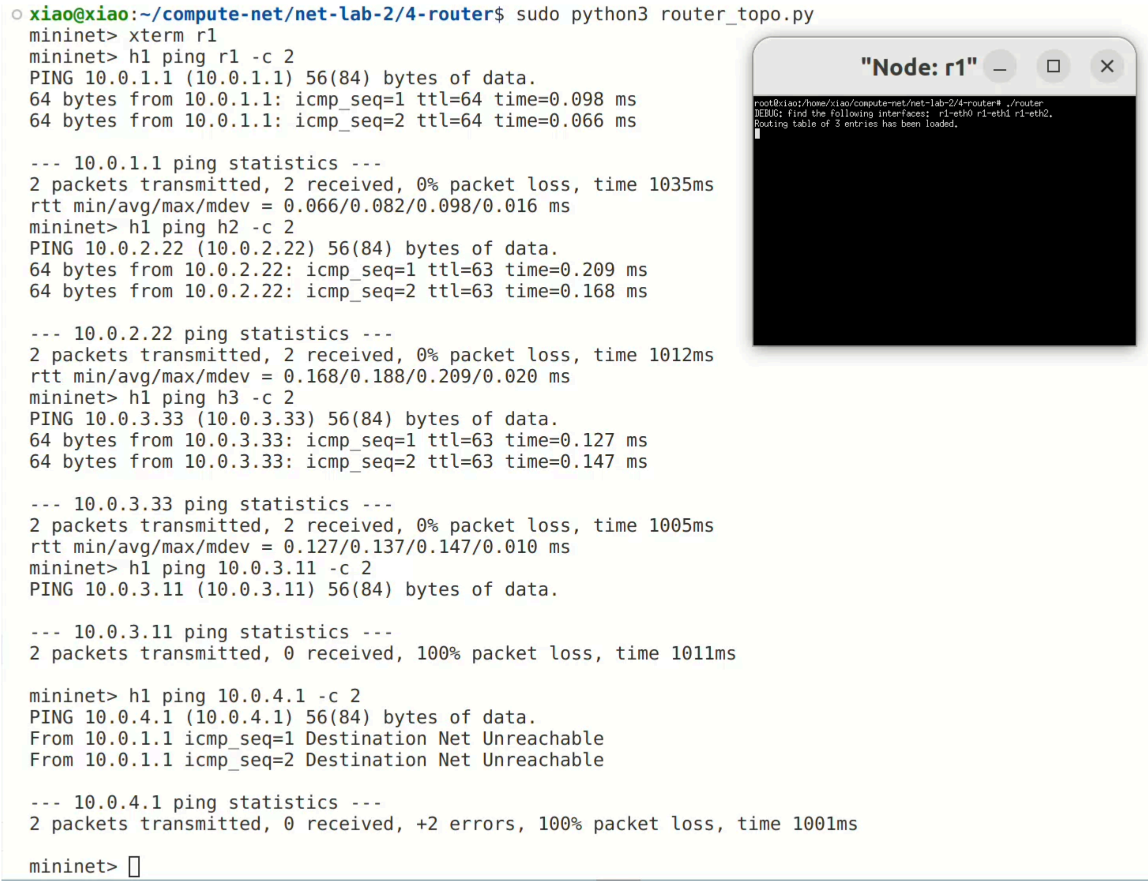
```
● xiao@xiao:~/compute-net/net-lab-2/4-router$ make clean
rm -f *.o router libipstack.a
● xiao@xiao:~/compute-net/net-lab-2/4-router$ make
gcc -c -g -Wall -Iinclude arp.c -o arp.o
gcc -c -g -Wall -Iinclude arpcache.c -o arpcache.o
In file included from arpcache.c:4:
include/icmp.h: In function ‘icmp_checksum’:
include/icmp.h:48:9: warning: converting a packed ‘struct icmphdr’ pointer (alignment 1) to a ‘u16’ {aka ‘short unsigned int’} pointer (alignment 2) may result in an unaligned pointer value [-Waddress-of-packed-member]
   48 |          u16 sum = checksum((u16 *)icmp, len, 0);
      |          ^~~
include/icmp.h:8:8: note: defined here
    8 | struct icmphdr {
      |        ^~~~~~~
arpcache.c: At top level:
arpcache.c:58:33: warning: argument 2 of type ‘u8[6]’ {aka ‘unsigned char[6]’} with mismatched bound [-Warray-parameter=]
   58 | int arpcache_lookup(u32 ip4, u8 mac[ETH_ALEN])
      |                              ~~~^~~~~~~~~~~~~
In file included from arpcache.c:1:
include/arpcache.h:47:33: note: previously declared as ‘u8[]’ {aka ‘unsigned char[]’}
   47 | int arpcache_lookup(u32 ip4, u8 mac[]);
      |                              ~~~^~~~~
arpcache.c:111:34: warning: argument 2 of type ‘u8[6]’ {aka ‘unsigned char[6]’} with mismatched bound [-Warray-parameter=]
  111 | void arpcache_insert(u32 ip4, u8 mac[ETH_ALEN])
      |                               ~~~^~~~~~~~~~~~~
include/arpcache.h:48:34: note: previously declared as ‘u8[]’ {aka ‘unsigned char[]’}
   48 | void arpcache_insert(u32 ip4, u8 mac[]);
      |                               ~~~^~~~~
gcc -c -g -Wall -Iinclude icmp.c -o icmp.o
In file included from icmp.c:1:
include/icmp.h: In function ‘icmp_checksum’:
include/icmp.h:48:9: warning: converting a packed ‘struct icmphdr’ pointer (alignment 1) to a ‘u16’ {aka ‘short unsigned int’} pointer (alignment 2) may result in an unaligned pointer value [-Waddress-of-packed-member]
   48 |          u16 sum = checksum((u16 *)icmp, len, 0);
      |          ^~~
include/icmp.h:8:8: note: defined here
    8 | struct icmphdr {
      |        ^~~~~~~
gcc -c -g -Wall -Iinclude ip_base.c -o ip_base.o
In file included from ip_base.c:2:
include/icmp.h: In function ‘icmp_checksum’:
include/icmp.h:48:9: warning: converting a packed ‘struct icmphdr’ pointer (alignment 1) to a ‘u16’ {aka ‘short unsigned int’} pointer (alignment 2) may result in an unaligned pointer value [-Waddress-of-packed-member]
   48 |          u16 sum = checksum((u16 *)icmp, len, 0);
```

修改 `Makefile`中的 `Cflag`，可以忽略 `warning`

```
# CFLAGS = -g -Wall -Iinclude
CFLAGS = -g -w -Iinclude
# CFLAGS = -g -Wall -Iinclude -Wno-address-of-packed-member -Wno-array-parameter
LDFLAGS = -L.
```

```
● xiao@xiao:~/compute-net/net-lab-2/4-router$ make clean
rm -f *.o router libipstack.a
● xiao@xiao:~/compute-net/net-lab-2/4-router$ make
gcc -c -g -w -Iinclude arp.c -o arp.o
gcc -c -g -w -Iinclude arpcache.c -o arpcache.o
gcc -c -g -w -Iinclude icmp.c -o icmp.o
gcc -c -g -w -Iinclude ip_base.c -o ip_base.o
gcc -c -g -w -Iinclude rtable.c -o rtable.o
gcc -c -g -w -Iinclude rtable_internal.c -o rtable_internal.o
gcc -c -g -w -Iinclude device_internal.c -o device_internal.o
ar rcs libipstack.a arp.o arpcache.o icmp.o ip_base.o rtable.o rtable_internal.o device_internal.o
gcc -c -g -w -Iinclude main.c -o main.o
gcc -c -g -w -Iinclude ip.c -o ip.o
gcc -L. main.o ip.o -o router -lipstack -lpthread
```

- 执行 `router_topo.py`脚本,在`r1`上启动`router`，在h1上分别`ping``r1`和 `h2`、`h3`以及`10.0.3.11`、`10.0.4.1`，得到如下结果：



结果分析如下:

Ping r1：``ping路由器入端口ip，能够ping通

Ping h1、h2：``ping能够连接到的节点，能够ping通

Ping 10.0.3.11: ``ping不存在的节点，返回ICMP Destination Host Unreachable

Ping 10.0.4.1：``ping不存在的网段，返回ICMP Destination Net Unreachable

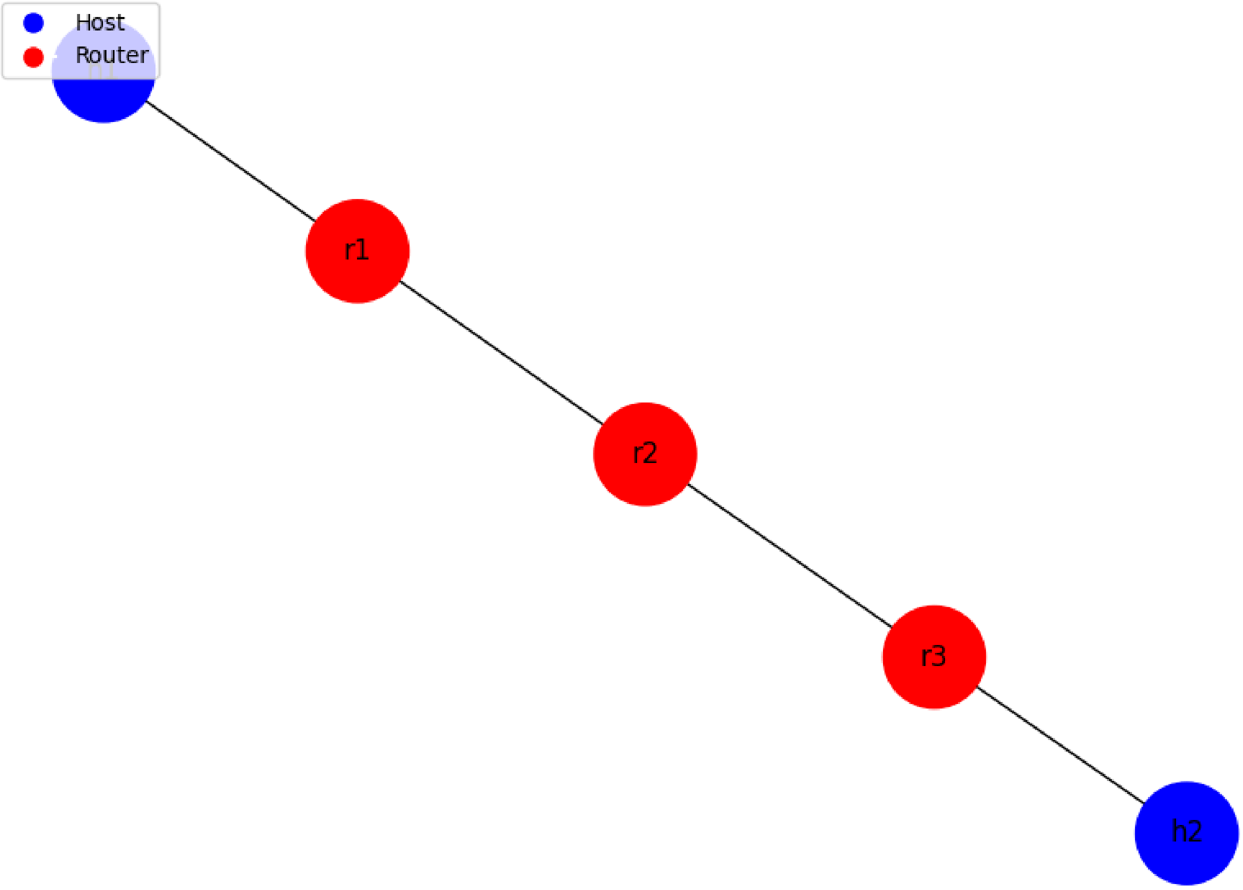
与理论结果相同，实验成功。

构造一个包含多个路由器节点组成的网络

连通性测试

路径测试

- 设计思路：我构造的拓扑结构如下图：



代码如下：

````
```python
from mininet.topo import Topo
from mininet.net import Mininet
from mininet.cli import CLI

class RouterTopo(Topo):
    def build(self):
        h1 = self.addHost('h1')
        h2 = self.addHost('h2')
        r1 = self.addHost('r1')
        r2 = self.addHost('r2')
        r3 = self.addHost('r3')

        self.addLink(h1, r1)
        self.addLink(r1, r2)
        self.addLink(r3, r2)
        self.addLink(r3, h2)

if __name__ == '__main__':
    topo = RouterTopo()
    net = Mininet(topo = topo, controller = None)

    h1, h2, r1, r2, r3 = net.get('h1', 'h2', 'r1', 'r2', 'r3')
    h1.cmd('ifconfig h1-eth0 10.0.1.11/24')
    h2.cmd('ifconfig h2-eth0 10.0.4.44/24')
````
````

```
    h1.cmd('route add default gw 10.0.1.1')
    h2.cmd('route add default gw 10.0.4.1')
    for h in (h1, h2):
        h.cmd('./scripts/disable_offloading.sh')
        h.cmd('./scripts/disable_ipv6.sh')

    r1.cmd('ifconfig r1-eth0 10.0.1.1/24')
    r1.cmd('ifconfig r1-eth1 10.0.2.2/24')
    r1.cmd('route add -net 10.0.4.0 netmask 255.255.255.0 gw 10.0.2.1 dev r1-eth1')
    r1.cmd('route add -net 10.0.3.0 netmask 255.255.255.0 gw 10.0.2.1 dev r1-eth1')

    r2.cmd('ifconfig r2-eth0 10.0.2.1/24')
    r2.cmd('ifconfig r2-eth1 10.0.3.1/24')
    r2.cmd('route add -net 10.0.1.0 netmask 255.255.255.0 gw 10.0.2.2 dev r2-eth0')
    r2.cmd('route add -net 10.0.4.0 netmask 255.255.255.0 gw 10.0.3.2 dev r2-eth1')

    r3.cmd('ifconfig r3-eth0 10.0.3.2/24')
    r3.cmd('ifconfig r3-eth1 10.0.4.1/24')
    r3.cmd('route add -net 10.0.1.0 netmask 255.255.255.0 gw 10.0.3.1 dev r3-eth0')
    r3.cmd('route add -net 10.0.2.0 netmask 255.255.255.0 gw 10.0.3.1 dev r3-eth0')

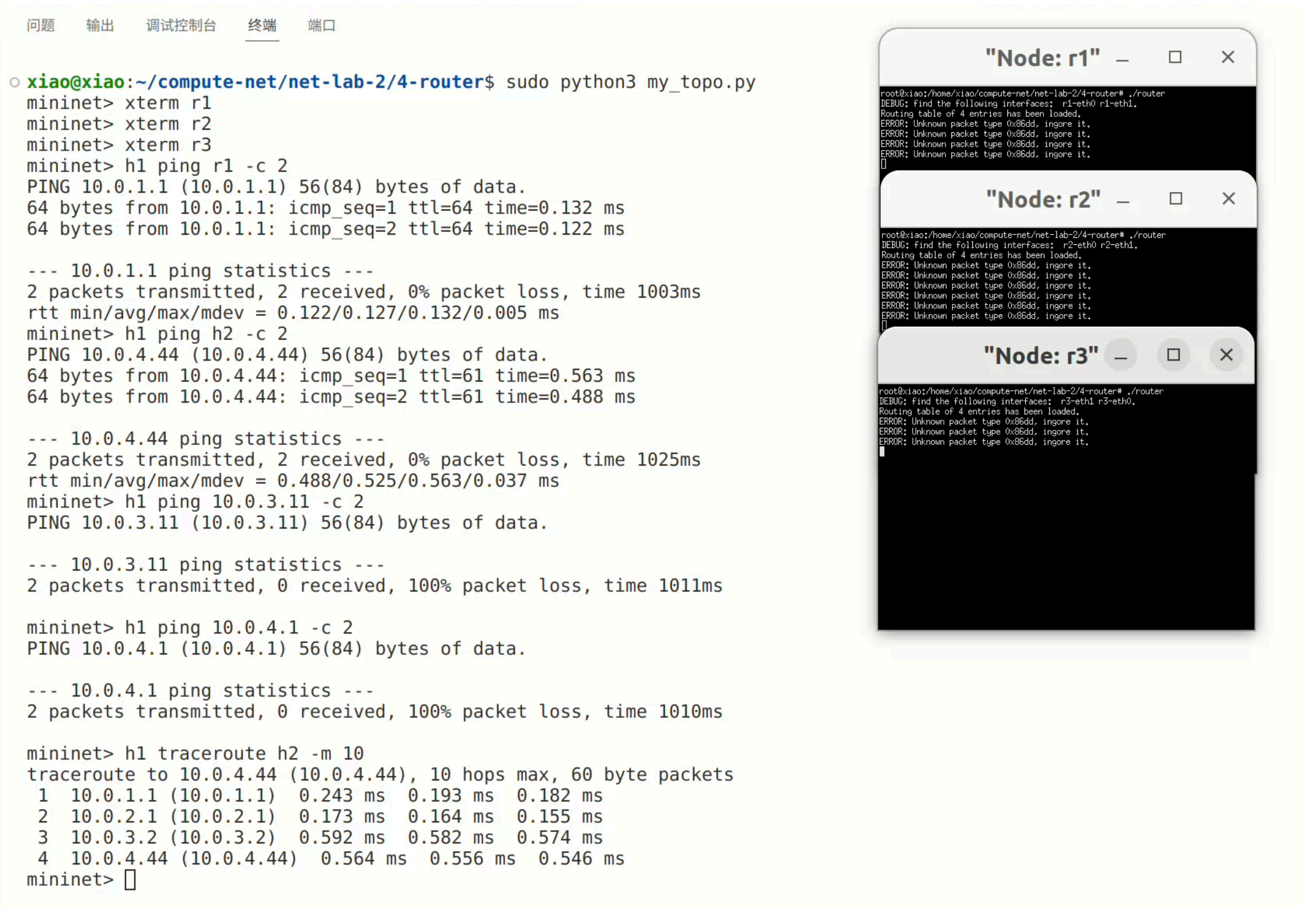
    r1.cmd('./scripts/disable_arp.sh')
    r1.cmd('./scripts/disable_icmp.sh')
    r1.cmd('./scripts/disable_ip_forward.sh')

    r2.cmd('./scripts/disable_arp.sh')
    r2.cmd('./scripts/disable_icmp.sh')
    r2.cmd('./scripts/disable_ip_forward.sh')

    r3.cmd('./scripts/disable_arp.sh')
    r3.cmd('./scripts/disable_icmp.sh')
    r3.cmd('./scripts/disable_ip_forward.sh')

    net.start()
    CLI(net)
    net.stop()
```

- 实验结果如下



结果分析:

结果分析如下:

`Ping r1`: `ping`路由器入端口`ip`，能够`ping`通

`Ping h1`: `ping`能够连接到的节点，能够`ping`通

`Ping 10.0.3.11`: `ping`不存在的节点，返回`ICMP Destination Host Unreachable`

`Ping 10.0.4.1`: `ping`不存在的网段，返回`ICMP Destination Net Unreachable`

在`h1`上`traceroute h2`，正确输出路径上每个节点的IP信息 与理论结果相同，实验成功。