

Лабораторная работа №5

Эмуляция и измерение потерь пакетов в глобальных сетях

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Информация

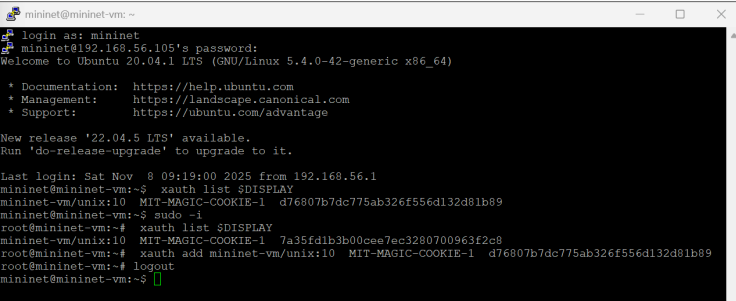
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Цель работы

Основной целью работы является получение навыков проведения интерактивных экспериментов в среде Mininet по исследованию параметров сети, связанных с потерей, дублированием, изменением порядка и повреждением пакетов при передаче данных. Эти параметры влияют на производительность протоколов и сетей.

Выполнение лабораторной работы

Исправление прав запуска X-соединения в виртуальной машине mininet



```
mininet@mininet-vm: ~  
login as: mininet  
mininet@192.168.56.105's password:  
Welcome to Ubuntu 20.04.1 LTS (GNU/Linux 5.4.0-42-generic x86_64)  
  
* Documentation:  https://help.ubuntu.com  
* Management:    https://landscape.canonical.com  
* Support:       https://ubuntu.com/advantage  
  
New release '22.04.5 LTS' available.  
Run 'do-release-upgrade' to upgrade to it.  
  
Last login: Sat Nov  8 09:19:00 2025 from 192.168.56.1  
mininet@mininet-vm:~$ xauth list $DISPLAY  
mininet-vm/unix:10  MIT-MAGIC-COOKIE-1  d76807b7dc775ab326f556d132d81b89  
mininet@mininet-vm:~$ sudo -i  
root@mininet-vm:~# xauth list $DISPLAY  
mininet-vm/unix:10  MIT-MAGIC-COOKIE-1  7a35fd1b3b00cea7ec3280700963f2c8  
root@mininet-vm:~# xauth add mininet-vm/unix:10  MIT-MAGIC-COOKIE-1  d76807b7dc775ab326f556d132d81b89  
root@mininet-vm:~# logout  
mininet@mininet-vm:~$
```

Рис. 1: Исправление прав запуска X-соединения в виртуальной машине mininet

Информация о сетевых интерфейсах и IP-адресах хостов

```
root@mininet-vm:/home/mininet# ifconfig
h1-eth0: flags=4163<UP,BROADCAST,RUNNING,MULTICAST> mtu 1500
    inet 10.0.0.1 netmask 255.0.0.0 broadcast 10.255.255.255
    ether e6:91:e5:ad:5b:60 txqueuelen 1000 (Ethernet)
    RX packets 0 bytes 0 (0.0 B)
    RX errors 0 dropped 0 overruns 0 frame 0
    TX packets 0 bytes 0 (0.0 B)
    TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0

lo: flags=73<UP,LOOPBACK,RUNNING> mtu 65536
    inet 127.0.0.1 netmask 255.0.0.0
    loop txqueuelen 1000 (Local Loopback)
    RX packets 1155 bytes 263912 (263.9 KB)
    RX errors 0 dropped 0 overruns 0 frame 0
    TX packets 1155 bytes 263912 (263.9 KB)
    TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0

root@mininet-vm:/home/mininet#
```

```
root@mininet-vm:/home/mininet# ifconfig
h2-eth0: flags=4163<UP,BROADCAST,RUNNING,MULTICAST> mtu 1500
    inet 10.0.0.2 netmask 255.0.0.0 broadcast 10.255.255.255
    ether 82:27:b6:24:b4:a5 txqueuelen 1000 (Ethernet)
    RX packets 0 bytes 0 (0.0 B)
    RX errors 0 dropped 0 overruns 0 frame 0
    TX packets 0 bytes 0 (0.0 B)
    TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0

lo: flags=73<UP,LOOPBACK,RUNNING> mtu 65536
    inet 127.0.0.1 netmask 255.0.0.0
    loop txqueuelen 1000 (Local Loopback)
    RX packets 1169 bytes 287148 (287.1 KB)
    RX errors 0 dropped 0 overruns 0 frame 0
    TX packets 1169 bytes 287148 (287.1 KB)
    TX errors 0 dropped 0 overruns 0 carrier 0 collisions 0

root@mininet-vm:/home/mininet#
```


Проверка подключения между хостами h1 и h2

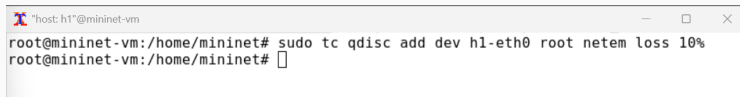
```
root@mininet-vm:/home/mininet# ping 10.0.0.2 -c 6
PING 10.0.0.2 (10.0.0.2) 56(84) bytes of data.
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=4.94 ms
64 bytes from 10.0.0.2: icmp_seq=2 ttl=64 time=0.217 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=0.066 ms
64 bytes from 10.0.0.2: icmp_seq=4 ttl=64 time=0.049 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=0.089 ms
64 bytes from 10.0.0.2: icmp_seq=6 ttl=64 time=0.087 ms

--- 10.0.0.2 ping statistics ---
6 packets transmitted, 6 received, 0% packet loss, time 5078ms
rtt min/avg/max/mdev = 0.049/0.908/4.940/1.803 ms
root@mininet-vm:/home/mininet#
```

```
root@mininet-vm:/home/mininet# ping 10.0.0.1 -c 6
PING 10.0.0.1 (10.0.0.1) 56(84) bytes of data.
64 bytes from 10.0.0.1: icmp_seq=1 ttl=64 time=3.10 ms
64 bytes from 10.0.0.1: icmp_seq=2 ttl=64 time=0.090 ms
64 bytes from 10.0.0.1: icmp_seq=3 ttl=64 time=0.047 ms
64 bytes from 10.0.0.1: icmp_seq=4 ttl=64 time=0.050 ms
64 bytes from 10.0.0.1: icmp_seq=5 ttl=64 time=0.057 ms
64 bytes from 10.0.0.1: icmp_seq=6 ttl=64 time=0.090 ms

--- 10.0.0.1 ping statistics ---
6 packets transmitted, 6 received, 0% packet loss, time 5089ms
rtt min/avg/max/mdev = 0.047/0.572/3.101/1.130 ms
root@mininet-vm:/home/mininet#
```

Добавление 10% потерь пакетов на хосте h1

A terminal window titled '"host: h1"@mininet-vm' with standard window controls. The prompt is 'root@mininet-vm:/home/mininet#'. The command 'sudo tc qdisc add dev h1-eth0 root netem loss 10%' is entered and executed. The prompt returns to 'root@mininet-vm:/home/mininet#' followed by a cursor.

```
"host: h1"@mininet-vm
root@mininet-vm:/home/mininet# sudo tc qdisc add dev h1-eth0 root netem loss 10%
root@mininet-vm:/home/mininet#
```

Рис. 4: Добавление 10% потерь пакетов на хосте h1

Проверка потерь пакетов 1

```
root@mininet-vm:~# ping -c 100 10.0.0.2
64 bytes from 10.0.0.2: icmp_seq=80 ttl=64 time=0.053 ms
64 bytes from 10.0.0.2: icmp_seq=81 ttl=64 time=0.083 ms
64 bytes from 10.0.0.2: icmp_seq=82 ttl=64 time=0.054 ms
64 bytes from 10.0.0.2: icmp_seq=83 ttl=64 time=0.056 ms
64 bytes from 10.0.0.2: icmp_seq=84 ttl=64 time=0.057 ms
64 bytes from 10.0.0.2: icmp_seq=86 ttl=64 time=0.094 ms
64 bytes from 10.0.0.2: icmp_seq=87 ttl=64 time=0.075 ms
64 bytes from 10.0.0.2: icmp_seq=88 ttl=64 time=0.089 ms
64 bytes from 10.0.0.2: icmp_seq=89 ttl=64 time=0.065 ms
64 bytes from 10.0.0.2: icmp_seq=90 ttl=64 time=0.072 ms
64 bytes from 10.0.0.2: icmp_seq=91 ttl=64 time=0.078 ms
64 bytes from 10.0.0.2: icmp_seq=92 ttl=64 time=0.052 ms
64 bytes from 10.0.0.2: icmp_seq=93 ttl=64 time=0.072 ms
64 bytes from 10.0.0.2: icmp_seq=94 ttl=64 time=0.078 ms
64 bytes from 10.0.0.2: icmp_seq=95 ttl=64 time=0.072 ms
64 bytes from 10.0.0.2: icmp_seq=96 ttl=64 time=0.079 ms
64 bytes from 10.0.0.2: icmp_seq=97 ttl=64 time=0.090 ms
64 bytes from 10.0.0.2: icmp_seq=98 ttl=64 time=0.059 ms
64 bytes from 10.0.0.2: icmp_seq=99 ttl=64 time=0.077 ms

--- 10.0.0.2 ping statistics ---
100 packets transmitted, 91 received, 9% packet loss, time 101335ms
rtt min/avg/max/mdev = 0.049/0.107/2.993/0.309 ms
root@mininet-vm:~#
```

Рис. 5: Проверка потерь пакетов 1

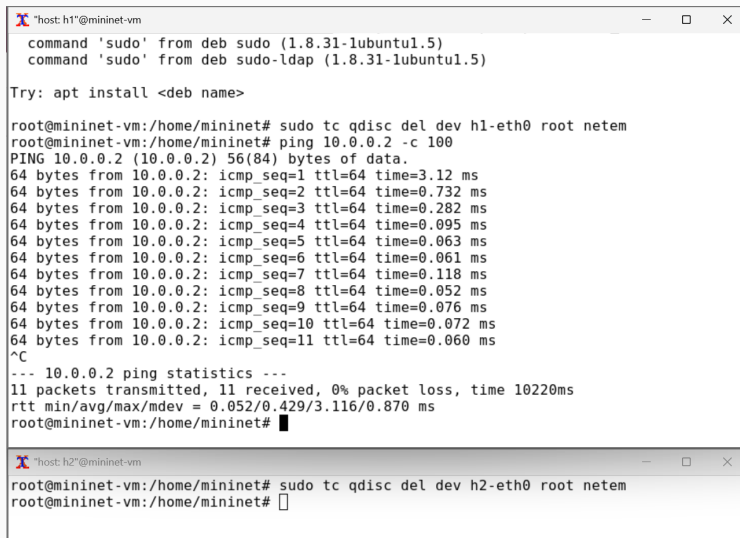
Проверка потерь пакетов 2

```
root@h11@mininet-vm
64 bytes from 10.0.0.2: icmp_seq=79 ttl=64 time=0.069 ms
64 bytes from 10.0.0.2: icmp_seq=80 ttl=64 time=0.065 ms
64 bytes from 10.0.0.2: icmp_seq=81 ttl=64 time=0.053 ms
64 bytes from 10.0.0.2: icmp_seq=83 ttl=64 time=0.067 ms
64 bytes from 10.0.0.2: icmp_seq=84 ttl=64 time=0.057 ms
64 bytes from 10.0.0.2: icmp_seq=85 ttl=64 time=0.054 ms
64 bytes from 10.0.0.2: icmp_seq=87 ttl=64 time=0.063 ms
64 bytes from 10.0.0.2: icmp_seq=88 ttl=64 time=0.062 ms
64 bytes from 10.0.0.2: icmp_seq=89 ttl=64 time=0.053 ms
64 bytes from 10.0.0.2: icmp_seq=90 ttl=64 time=0.067 ms
64 bytes from 10.0.0.2: icmp_seq=92 ttl=64 time=0.084 ms
64 bytes from 10.0.0.2: icmp_seq=93 ttl=64 time=0.065 ms
64 bytes from 10.0.0.2: icmp_seq=94 ttl=64 time=0.062 ms
64 bytes from 10.0.0.2: icmp_seq=95 ttl=64 time=0.056 ms
64 bytes from 10.0.0.2: icmp_seq=96 ttl=64 time=0.076 ms
64 bytes from 10.0.0.2: icmp_seq=97 ttl=64 time=0.055 ms
64 bytes from 10.0.0.2: icmp_seq=98 ttl=64 time=0.067 ms
64 bytes from 10.0.0.2: icmp_seq=99 ttl=64 time=0.075 ms
64 bytes from 10.0.0.2: icmp_seq=100 ttl=64 time=0.062 ms

--- 10.0.0.2 ping statistics ---
100 packets transmitted, 80 received, 20% packet loss, time 101335ms
rtt min/avg/max/mdev = 0.051/0.106/2.294/0.251 ms
root@mininet-vm:/home/mininet#

root@h22@mininet-vm
root@mininet-vm:/home/mininet# sudo tc qdisc add dev h2-eth0 root netem loss 10%
root@mininet-vm:/home/mininet#
```

Восстановление конфигурации по умолчанию для хоста h1 и хоста h2 и проверка



```
"host: h1"@mininet-vm
command 'sudo' from deb sudo (1.8.31-1ubuntu1.5)
command 'sudo' from deb sudo-ldap (1.8.31-1ubuntu1.5)

Try: apt install <deb name>

root@mininet-vm:/home/mininet# sudo tc qdisc del dev h1-eth0 root netem
root@mininet-vm:/home/mininet# ping 10.0.0.2 -c 100
PING 10.0.0.2 (10.0.0.2) 56(84) bytes of data.
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=3.12 ms
64 bytes from 10.0.0.2: icmp_seq=2 ttl=64 time=0.732 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=0.282 ms
64 bytes from 10.0.0.2: icmp_seq=4 ttl=64 time=0.095 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=0.063 ms
64 bytes from 10.0.0.2: icmp_seq=6 ttl=64 time=0.061 ms
64 bytes from 10.0.0.2: icmp_seq=7 ttl=64 time=0.118 ms
64 bytes from 10.0.0.2: icmp_seq=8 ttl=64 time=0.052 ms
64 bytes from 10.0.0.2: icmp_seq=9 ttl=64 time=0.076 ms
64 bytes from 10.0.0.2: icmp_seq=10 ttl=64 time=0.072 ms
64 bytes from 10.0.0.2: icmp_seq=11 ttl=64 time=0.060 ms
^C
--- 10.0.0.2 ping statistics ---
11 packets transmitted, 11 received, 0% packet loss, time 10220ms
rtt min/avg/max/mdev = 0.052/0.429/3.116/0.870 ms
root@mininet-vm:/home/mininet# █

"host: h2"@mininet-vm
root@mininet-vm:/home/mininet# sudo tc qdisc del dev h2-eth0 root netem
root@mininet-vm:/home/mininet# █
```

Добавление значения корреляции для потери пакетов и тест

```
"host: h1"@mininet-vm
root@mininet-vm:/home/mininet#
root@mininet-vm:/home/mininet#
root@mininet-vm:/home/mininet#
root@mininet-vm:/home/mininet#
root@mininet-vm:/home/mininet#
root@mininet-vm:/home/mininet# sudo tc qdisc add dev h1-eth0 root netem loss 50% 50
%
root@mininet-vm:/home/mininet# ping 10.0.0.2 -c 50
PING 10.0.0.2 (10.0.0.2) 56(84) bytes of data.
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=2.82 ms
64 bytes from 10.0.0.2: icmp_seq=2 ttl=64 time=0.432 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=0.190 ms
64 bytes from 10.0.0.2: icmp_seq=4 ttl=64 time=0.053 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=0.067 ms
64 bytes from 10.0.0.2: icmp_seq=6 ttl=64 time=0.062 ms
64 bytes from 10.0.0.2: icmp_seq=7 ttl=64 time=0.077 ms
64 bytes from 10.0.0.2: icmp_seq=8 ttl=64 time=0.056 ms
64 bytes from 10.0.0.2: icmp_seq=9 ttl=64 time=0.084 ms
64 bytes from 10.0.0.2: icmp_seq=10 ttl=64 time=0.075 ms
64 bytes from 10.0.0.2: icmp_seq=11 ttl=64 time=0.077 ms
64 bytes from 10.0.0.2: icmp_seq=18 ttl=64 time=0.096 ms
64 bytes from 10.0.0.2: icmp_seq=20 ttl=64 time=0.100 ms
64 bytes from 10.0.0.2: icmp_seq=25 ttl=64 time=0.084 ms
64 bytes from 10.0.0.2: icmp_seq=26 ttl=64 time=0.078 ms
64 bytes from 10.0.0.2: icmp_seq=30 ttl=64 time=0.083 ms
64 bytes from 10.0.0.2: icmp_seq=42 ttl=64 time=0.206 ms
64 bytes from 10.0.0.2: icmp_seq=47 ttl=64 time=0.073 ms
64 bytes from 10.0.0.2: icmp_seq=50 ttl=64 time=0.070 ms

--- 10.0.0.2 ping statistics ---
50 packets transmitted, 19 received, 62% packet loss, time 50146ms
rtt min/avg/max/mdev = 0.053/0.251/2.815/0.610 ms
root@mininet-vm:/home/mininet#
```

Добавление на узле h1 0.01% повреждения пакетов и проверка через iperf

```
root@mininet-vm:/home/mininet# sudo tc qdisc add dev h1-eth0 root netem corrupt 0.01%
root@mininet-vm:/home/mininet# iperf3 -c 10.0.0.2
iperf3: error - unable to connect to server: Connection refused
root@mininet-vm:/home/mininet# iperf3 -c 10.0.0.2
iperf3: error - unable to connect to server: Connection refused
root@mininet-vm:/home/mininet# iperf3 -c 10.0.0.2
Connecting to host 10.0.0.2, port 5201
[ 7] local 10.0.0.1 port 35450 connected to 10.0.0.2 port 5201
[ ID] Interval      Transfer    Bitrate      Retr  Cwnd
[ 7]  0.00-1.01 sec  1.16 GBytes  9.86 Gbits/sec    1   5.69 MBytes
[ 7]  1.01-2.01 sec  1.30 GBytes 11.2 Gbits/sec    2   2.92 MBytes
[ 7]  2.01-3.01 sec  1.29 GBytes 11.2 Gbits/sec    4   1.38 MBytes
[ 7]  3.01-4.00 sec  1.88 GBytes 16.3 Gbits/sec    1   2.36 MBytes
[ 7]  4.00-5.00 sec  1.45 GBytes 12.4 Gbits/sec    3   1.19 MBytes
[ 7]  5.00-6.00 sec  1.16 GBytes 10.0 Gbits/sec    1   1.17 MBytes
[ 7]  6.00-7.00 sec  1.20 GBytes 10.3 Gbits/sec    1   1.31 MBytes
[ 7]  7.00-8.00 sec  1.30 GBytes 11.2 Gbits/sec    6    831 KBytes
[ 7]  8.00-9.00 sec  1.27 GBytes 10.9 Gbits/sec    4   1.02 MBytes
[ 7]  9.00-10.01 sec 1.48 GBytes 12.6 Gbits/sec    3   1.36 MBytes
-----
[ ID] Interval      Transfer    Bitrate      Retr
[ 7]  0.00-10.01 sec 13.5 GBytes 11.6 Gbits/sec    26
[ 7]  0.00-10.01 sec 13.5 GBytes 11.6 Gbits/sec

iperf Done.
root@mininet-vm:/home/mininet#
```

```
Accepted connection from 10.0.0.1, port 35448
[ 7] local 10.0.0.2 port 5201 connected to 10.0.0.1 port 35450
[ ID] Interval      Transfer    Bitrate
[ 7]  0.00-1.00 sec  1.15 GBytes  9.86 Gbits/sec
[ 7]  1.00-2.01 sec  1.30 GBytes 11.1 Gbits/sec
[ 7]  2.01-3.00 sec  1.30 GBytes 11.3 Gbits/sec
[ 7]  3.00-4.00 sec  1.89 GBytes 16.2 Gbits/sec
[ 7]  4.00-5.00 sec  1.44 GBytes 12.4 Gbits/sec
[ 7]  5.00-6.01 sec  1.15 GBytes  9.79 Gbits/sec
[ 7]  6.01-7.00 sec  1.23 GBytes 10.6 Gbits/sec
[ 7]  7.00-8.00 sec  1.28 GBytes 11.0 Gbits/sec
[ 7]  8.00-9.00 sec  1.28 GBytes 11.1 Gbits/sec
[ 7]  9.00-10.00 sec  1.47 GBytes 12.6 Gbits/sec
[ 7] 10.00-10.01 sec 11.1 MBytes  7.27 Gbits/sec
-----
[ ID] Interval      Transfer    Bitrate
[ 7]  0.00-10.01 sec 13.5 GBytes 11.6 Gbits/sec
-----
receiver

Server listening on 5201
^Ciperf3: interrupt - the server has terminated
```

Добавление переупорядочивания пакетов и тест

```
root@mininet-vm:/home/mininet# sudo tc qdisc del dev h1-eth0 root netem
Error: Invalid qdisc name.
root@mininet-vm:/home/mininet# sudo tc qdisc add dev h1-eth0 root netem delay 10ms
reorder 25% 50%
root@mininet-vm:/home/mininet# ping 10.0.0.2 -c 20
PING 10.0.0.2 (10.0.0.2) 56(84) bytes of data.
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=11.9 ms
64 bytes from 10.0.0.2: icmp_seq=2 ttl=64 time=1.13 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=0.241 ms
64 bytes from 10.0.0.2: icmp_seq=4 ttl=64 time=10.8 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=10.2 ms
64 bytes from 10.0.0.2: icmp_seq=6 ttl=64 time=10.7 ms
64 bytes from 10.0.0.2: icmp_seq=7 ttl=64 time=10.6 ms
64 bytes from 10.0.0.2: icmp_seq=8 ttl=64 time=10.7 ms
64 bytes from 10.0.0.2: icmp_seq=9 ttl=64 time=0.152 ms
64 bytes from 10.0.0.2: icmp_seq=10 ttl=64 time=11.0 ms
64 bytes from 10.0.0.2: icmp_seq=11 ttl=64 time=10.5 ms
64 bytes from 10.0.0.2: icmp_seq=12 ttl=64 time=10.3 ms
64 bytes from 10.0.0.2: icmp_seq=13 ttl=64 time=10.6 ms
64 bytes from 10.0.0.2: icmp_seq=14 ttl=64 time=0.081 ms
64 bytes from 10.0.0.2: icmp_seq=15 ttl=64 time=11.1 ms
64 bytes from 10.0.0.2: icmp_seq=16 ttl=64 time=10.4 ms
64 bytes from 10.0.0.2: icmp_seq=17 ttl=64 time=37.0 ms
64 bytes from 10.0.0.2: icmp_seq=18 ttl=64 time=11.2 ms
64 bytes from 10.0.0.2: icmp_seq=19 ttl=64 time=10.6 ms
64 bytes from 10.0.0.2: icmp_seq=20 ttl=64 time=0.075 ms

--- 10.0.0.2 ping statistics ---
20 packets transmitted, 20 received, 0% packet loss, time 19074ms
rtt min/avg/max/mdev = 0.075/9.470/37.048/7.760 ms
root@mininet-vm:/home/mininet#
```

Рис. 10: Добавление переупорядочивания пакетов и тест

Добавление дублирования пакетов и тест

```
root@mininet-vm:/home/mininet# sudo tc qdisc del dev h1-eth0 root netem
root@mininet-vm:/home/mininet# sudo tc qdisc add dev h1-eth0 root netem duplicate 5
0%
root@mininet-vm:/home/mininet# ping 10.0.0.2 -c 20
PING 10.0.0.2 (10.0.0.2) 56(84) bytes of data.
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=4.73 ms
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=6.19 ms (DUP!)
64 bytes from 10.0.0.2: icmp_seq=2 ttl=64 time=0.485 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=0.299 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=0.776 ms (DUP!)
64 bytes from 10.0.0.2: icmp_seq=4 ttl=64 time=0.065 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=0.055 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=0.055 ms (DUP!)
64 bytes from 10.0.0.2: icmp_seq=6 ttl=64 time=0.061 ms
64 bytes from 10.0.0.2: icmp_seq=7 ttl=64 time=0.073 ms
64 bytes from 10.0.0.2: icmp_seq=7 ttl=64 time=0.073 ms (DUP!)
64 bytes from 10.0.0.2: icmp_seq=8 ttl=64 time=0.078 ms
64 bytes from 10.0.0.2: icmp_seq=9 ttl=64 time=0.060 ms
64 bytes from 10.0.0.2: icmp_seq=10 ttl=64 time=0.054 ms
64 bytes from 10.0.0.2: icmp_seq=11 ttl=64 time=0.069 ms
64 bytes from 10.0.0.2: icmp_seq=11 ttl=64 time=0.069 ms (DUP!)
64 bytes from 10.0.0.2: icmp_seq=12 ttl=64 time=0.075 ms
64 bytes from 10.0.0.2: icmp_seq=13 ttl=64 time=0.065 ms
64 bytes from 10.0.0.2: icmp_seq=13 ttl=64 time=0.065 ms (DUP!)
64 bytes from 10.0.0.2: icmp_seq=14 ttl=64 time=0.089 ms
64 bytes from 10.0.0.2: icmp_seq=15 ttl=64 time=0.068 ms
64 bytes from 10.0.0.2: icmp_seq=16 ttl=64 time=0.049 ms
64 bytes from 10.0.0.2: icmp_seq=17 ttl=64 time=0.063 ms
64 bytes from 10.0.0.2: icmp_seq=18 ttl=64 time=0.066 ms
64 bytes from 10.0.0.2: icmp_seq=19 ttl=64 time=0.066 ms
64 bytes from 10.0.0.2: icmp_seq=19 ttl=64 time=0.067 ms (DUP!)
64 bytes from 10.0.0.2: icmp_seq=20 ttl=64 time=0.065 ms

--- 10.0.0.2 ping statistics ---
20 packets transmitted, 20 received, +7 duplicates, 0% packet loss, time 19436ms
rtt min/avg/max/mdev = 0.049/0.516/6.193/1.421 ms
root@mininet-vm:/home/mininet#
```

Листинг lab_netem_ii для simple-drop из лабораторной

```
mininet@mininet-vm: ~/work/lab_netem_ii/simple-drop
GNU nano 4.8 lab_netem_ii.py Modified
#!/usr/bin/env python

from mininet.net import Mininet
from mininet.node import Controller
from mininet.cli import CLI
from mininet.log import setLogLevel, info
import time

def emptyNet():

    net = Mininet( controller=Controller, waitConnected=True )
    info( '*** Adding controller\n' )
    net.addController( 'c0' )

    info( '*** Adding hosts\n' )
    h1 = net.addHost( 'h1', ip='10.0.0.1' )
    h2 = net.addHost( 'h2', ip='10.0.0.2' )

    info( '*** Adding switch\n' )
    s1 = net.addSwitch( 's1' )

    info( '*** Creating links\n' )
    net.addLink( h1, s1 )
    net.addLink( h2, s1 )

    info( '*** Starting network\n' )
    net.start()

    info( '*** Set delay\n' )
    h1.cmdPrint( 'tc qdisc add dev h1-eth0 root netem loss 10%' )
    h2.cmdPrint( 'tc qdisc add dev h2-eth0 root netem loss 10%' )

    time.sleep(10) # Wait 10 seconds

    info( '*** Ping\n' )
    h1.cmdPrint( 'ping -c 100', h2.IP(), '| grep "time=" | awk \'{print $5, $7}\'} | sed -e \'s/time>

    info( '*** Stopping network' )
    net.stop()

if __name__ == '__main__':
    setLogLevel( 'info' )
    emptyNet()
```

Листинг lab_netem_ii для simple-drop с анализом

```
mininet@mininet-vm: ~/work/lab_netem_ii/simple-drop
GNU nano 4.8 lab_netem_ii.py Modified
#!/usr/bin/env python

from mininet.net import Mininet
from mininet.node import Controller
from mininet.cli import CLI
from mininet.log import setLogLevel, info
import time

def analyze_ping_data(file_path='ping.dat', total_packets=100):
    if total_packets <= 0:
        print("ERROR")
        return

    received_packets = set()

    with open(file_path, 'r') as f:
        for line in f:
            parts = line.split()
            if parts:
                try:
                    packet_n = int(parts[0])
                    received_packets.add(packet_n)
                except ValueError:
                    pass

    lost_packets = [i for i in range(1, total_packets + 1) if i not in received_packets]
    lost_packets_count = len(lost_packets)
    loss_percent = (lost_packets_count / total_packets) * 100

    print(f'Total packets: {total_packets}')
    print(f'Received packets count: {len(received_packets)}')
    print(f'Lost packets count: {lost_packets_count}')
    print(f'Lost packets: {sorted(lost_packets)}')
    print(f'Loss packets percent: {loss_percent:.2f}%')

def emptyNet():
    net = Mininet( controller=Controller, waitConnected=True )
    info( '*** Adding controller\n' )
    net.addController( 'c0' )

    info( '*** Adding hosts\n' )
    h1 = net.addHost( 'h1', ip='10.0.0.1' )
    h2 = net.addHost( 'h2', ip='10.0.0.2' )

    info( '*** Adding switch\n' )
    s1 = net.addSwitch( 's1' )

    info( '*** Creating links\n' )
    net.addLink( h1, s1 )
    net.addLink( h2, s1 )

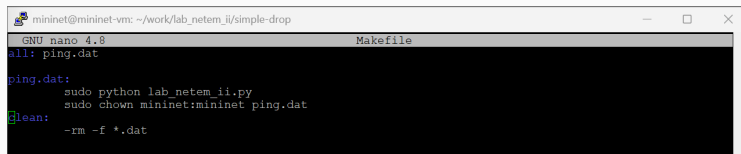
    info( '*** Starting network\n' )
    net.start()

    info( '*** Set delay\n' )
    h1.cmdPrint( 'tc qdisc add dev h1-eth0 root netem loss 10%' )
    h2.cmdPrint( 'tc qdisc add dev h2-eth0 root netem loss 10%' )

    time.sleep(10) # Wait 10 seconds

    info( '*** Finished\n' )
```

Листинг Makefile для simple-drop



The screenshot shows a terminal window with the title bar "mininet@mininet-vm: ~/work/lab_netem_ii/simple-drop". The window contains the GNU nano 4.8 editor editing a file named "Makefile". The content of the Makefile is as follows:

```
all: ping.dat

ping.dat:
    sudo python lab_netem_ii.py
    sudo chown mininet:mininet ping.dat

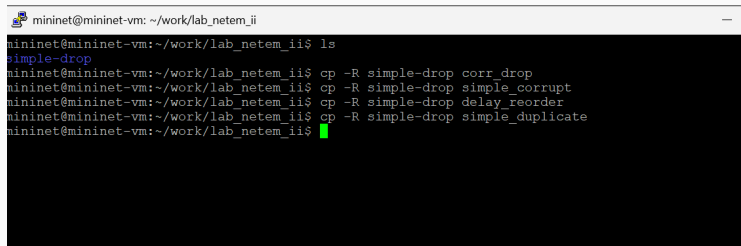
clean:
    -rm -f *.dat
```

Рис. 14: Листинг Makefile для simple-drop

Выполнение эксперимента и последующая очистка каталога

```
mininet@mininet-vm: ~/work/lab_netem_ii/simple-drop
mininet@mininet-vm:~/work/lab_netem_ii/simple-drop$ make
sudo python lab_netem_ii.py
File "lab_netem_ii.py", line 17
    lost_packets = set([for i in range(1, total_packets+1) if i not in received_packets])
                        ^
SyntaxError: invalid syntax
make: *** [Makefile:4: ping.dat] Error 1
mininet@mininet-vm:~/work/lab_netem_ii/simple-drop$ nano lab_netem_ii.py
mininet@mininet-vm:~/work/lab_netem_ii/simple-drop$ make
sudo python lab_netem_ii.py
File "lab_netem_ii.py", line 17
    lost_packets = set([for i in range(1, total_packets+1) if i not in received_packets])
                        ^
SyntaxError: invalid syntax
make: *** [Makefile:4: ping.dat] Error 1
mininet@mininet-vm:~/work/lab_netem_ii/simple-drop$ nano lab_netem_ii.py
mininet@mininet-vm:~/work/lab_netem_ii/simple-drop$ make
sudo python lab_netem_ii.py
*** Adding controller
*** Adding hosts
*** Adding switch
*** Creating links
*** Starting network
*** Configuring hosts
h1 h2
*** Starting controller
c0
*** Starting 1 switches
s1 ...
*** Waiting for switches to connect
c1
*** Set delay
*** h1 : ('tc qdisc add dev h1-eth0 root netem loss 10%',)
*** h2 : ('tc qdisc add dev h2-eth0 root netem loss 10%',)
*** Ping
*** h1 : ('ping -c 100', '10.0.0.2', '| grep "time=" | awk \'(print $5, $7)\' | sed -e \'s/time=//g\' -e
\'s/icmp_seq=//g\' > ping.dat')
Total packets: 100
Received packets count: 74
Lost packets count: 26
Lost packets: [1, 3, 4, 5, 6, 10, 23, 29, 32, 33, 34, 38, 46, 50, 55, 56, 63, 65, 67, 70, 73, 82, 84, 90
, 94, 95]
Loss packets percent: 26.00%
*** Stopping network*** Stopping 1 controllers
c0
*** Stopping 2 links
..
*** Stopping 1 switches
s1
*** Stopping 2 hosts
h1 h2
*** Done
sudo chown mininet:mininet ping.dat
mininet@mininet-vm:~/work/lab_netem_ii/simple-drop$ make clean
rm -f *.dat
```

Создание каталогов для самостоятельной работы

A terminal window with a title bar showing the user 'mininet' on a host 'mininet-vm' at the directory '~/work/lab_netem_ii'. The terminal output shows a sequence of commands and their results. First, 'ls' is run, showing 'simple-drop' in blue. Then, four 'cp -R' commands are executed to create subdirectories: 'corr_drop', 'simple_corrupt', 'delay_reorder', and 'simple_duplicate'. Each command is followed by a new prompt line.

```
mininet@mininet-vm: ~/work/lab_netem_ii
mininet@mininet-vm:~/work/lab_netem_ii$ ls
simple-drop
mininet@mininet-vm:~/work/lab_netem_ii$ cp -R simple-drop corr_drop
mininet@mininet-vm:~/work/lab_netem_ii$ cp -R simple-drop simple_corrupt
mininet@mininet-vm:~/work/lab_netem_ii$ cp -R simple-drop delay_reorder
mininet@mininet-vm:~/work/lab_netem_ii$ cp -R simple-drop simple_duplicate
mininet@mininet-vm:~/work/lab_netem_ii$
```

Рис. 16: Создание каталогов для самостоятельной работы

Листинг программы для эксперимента по добавлению потери и коэффициента корреляции

```
mininet@mininet-vm: ~/work/lab_netem_i/corr_drop
GNU nano 4.8 lab_netem_i1.py Modified
return

received_packets = set()

with open(file_path, 'r') as f:
    for line in f:
        parts = line.split()
        if parts:
            try:
                packet_n = int(parts[0])
                received_packets.add(packet_n)
            except ValueError:
                pass

lost_packets = [i for i in range(1, total_packets + 1) if i not in received_packets]
lost_packets_count = len(lost_packets)
loss_percent = (lost_packets_count / total_packets) * 100

print(f'Total packets: {total_packets}')
print(f'Received packets count: {len(received_packets)}')
print(f'Lost packets count: {lost_packets_count}')
print(f'Lost packets: {sorted(lost_packets)}')
print(f'Loss packets percent: {loss_percent:.2f}%')

def emptyNet():
    net = Mininet( controller=Controller, waitConnected=True )
    info( '*** Adding controller\n' )
    net.addController( 'c0' )

    info( '*** Adding hosts\n' )
    h1 = net.addHost( 'h1', ip='10.0.0.1' )
    h2 = net.addHost( 'h2', ip='10.0.0.2' )

    info( '*** Adding switch\n' )
    s1 = net.addSwitch( 's1' )

    info( '*** Creating links\n' )
    net.addLink( h1, s1 )
    net.addLink( h2, s1 )

    info( '*** Starting network\n' )
    net.start()

    info( '*** Set delay\n' )
    h1.cmdPrint( 'tc qdisc add dev h1-eth0 root netem loss 50% 50%' )
    h2.cmdPrint( 'tc qdisc add dev h2-eth0 root netem loss 10%' )

    time.sleep(10) # Wait 10 seconds

    info( '*** Ping\n' )
    h1.cmdPrint( 'ping -c 100', h2.IP(), '| grep "time=" | awk \'{print $5, $7}\'' | sed -e 's/time=/' )

    analyze_ping_data()

    info( '*** Stopping network\n' )
    net.stop()

if __name__ == '__main__':
    setLogLevel( 'info' )
    emptyNet()
```

Выполнение эксперимента по добавлению потери и коэффициента корреляции

```
mininet@mininet-vm: ~/work/lab_netem_ii/corr_drop
mininet@mininet-vm:~/work/lab_netem_ii$ ls
corr_drop  delay_reorder  simple_corrupt  simple-drop  simple_duplicate
mininet@mininet-vm:~/work/lab_netem_ii$ cd corr_drop
mininet@mininet-vm:~/work/lab_netem_ii/corr_drop$ nano lab_netem_ii.py
mininet@mininet-vm:~/work/lab_netem_ii/corr_drop$ make
sudo python lab_netem_ii.py
*** Adding controller
*** Adding hosts
*** Adding switch
*** Creating links
*** Starting network
*** Configuring hosts
h1 h2
*** Starting controller
c0
*** Starting 1 switches
s1 ...
*** Waiting for switches to connect
s1
*** Set delay
*** h1 : ('tc qdisc add dev h1-eth0 root netem loss 50% 50%',)
*** Ping
*** h1 : ('ping -c 100', '10.0.0.2', '| grep "time=" | awk \'{print $5, $7}\'' | sed -e \'s/time=//g\' -e \'s/icmp_seq=//g\' > ping.dat')
Total packets: 100
Received packets count: 39
Lost packets count: 61
Lost packets: [1, 2, 3, 4, 5, 6, 9, 10, 11, 12, 14, 16, 17, 18, 19, 20, 23, 24, 25, 26, 27, 28, 30, 31, 33, 34, 37, 41, 42, 43, 46, 47, 51, 52, 53, 54, 61, 65, 66, 67, 68, 69, 70, 71, 72, 74, 75, 77, 78, 80, 81, 82, 83, 85, 86, 88, 90, 91, 94, 95, 99]
Loss packets percent: 61.00%
*** Stopping network*** Stopping 1 controllers
c0
*** Stopping 2 links
..
*** Stopping 1 switches
s1
*** Stopping 2 hosts
h1 h2
*** Done
sudo chown mininet:mininet ping.dat
mininet@mininet-vm:~/work/lab_netem_ii/corr_drop$
```


Листинг программы для эксперимента по повреждению пакетов

```
mininet@mininet-vm: ~/work/lab_netem_ii/simple_corrupt
GNU nano 4.8 lab_netem_ii.py
#!/usr/bin/env python
from mininet.net import Mininet
from mininet.node import Controller
from mininet.log import setLogLevel
import time

def analyze_corrupt(file='iperf_result.txt'):
    print("=== Packet Corruption Analysis ===")
    total_retr = 0
    with open(file) as f:
        for line in f:
            parts = line.split()
            if len(parts) >= 9 and parts[-3].isdigit():
                total_retr += int(parts[-3])
    print(f"Total TCP retransmissions: {total_retr}")

def experiment():
    net = Mininet(controller=Controller, waitConnected=True)
    net.addController('c0')

    h1 = net.addHost('h1', ip='10.0.0.1')
    h2 = net.addHost('h2', ip='10.0.0.2')
    s1 = net.addSwitch('s1')
    net.addLink(h1, s1)
    net.addLink(h2, s1)
    net.start()

    h1.cmd('tc qdisc add dev h1-eth0 root netem corrupt 0.01%')

    h2.cmd('iperf3 -s > /tmp/iperf_srv.log 2>&1 &')
    time.sleep(1)

    h1.cmd(f'iperf3 -c {h2.IP()} > iperf_result.txt')

    analyze_corrupt()
    net.stop()

if __name__ == "__main__":
    setLogLevel("info")
    experiment()
```

Выполнение эксперимента по повреждению пакетов

```
mininet@mininet-vm:~/work/lab_netem_ii/simple_corrupt$ make
sudo python lab_netem_ii.py
*** Configuring hosts
h1 h2
*** Starting controller
c0
*** Starting 1 switches
s1 ...
*** Waiting for switches to connect
s1
=== Packet Corruption Analysis ===
Total TCP retransmissions: 32
*** Stopping 1 controllers
c0
*** Stopping 2 links
..
*** Stopping 1 switches
s1
*** Stopping 2 hosts
h1 h2
*** Done
```

Рис. 20: Выполнение эксперимента по повреждению пакетов

Листинг программы для эксперимента по изменению порядка пакетов

```
mininet@mininet-vm: ~/work/lab_netem_ii/delay_reorder
GNU nano 4.8 lab_netem_ii.py
#!/usr/bin/env python
from mininet.net import Mininet
from mininet.node import Controller
from mininet.log import setLogLevel
import time

def analyze_reorder(file='reorder.dat'):
    delays = []
    with open(file, 'r') as f:
        for line in f:
            try:
                rtt = float(line.strip())
                delays.append(rtt)
            except:
                pass
    if not delays:
        print("No data found.")
        return
    threshold = min(delays) + 5
    fast = [d for d in delays if d < threshold]
    slow = [d for d in delays if d >= threshold]

    print("=== Packet Reordering Analysis ===")
    print(f"Total packets: {len(delays)}")
    print(f"Fast path (~no delay): {len(fast)}")
    print(f"Slow path (~delayed): {len(slow)}")
    print(f"Avg fast RTT: {sum(fast)/len(fast):.3f} ms")
    print(f"Avg slow RTT: {sum(slow)/len(slow):.3f} ms")

def experiment():
    net = Mininet(controller=Controller, waitConnected=True)
    net.addController('c0')
    h1 = net.addHost('h1', ip='10.0.0.1')
    h2 = net.addHost('h2', ip='10.0.0.2')
    s1 = net.addSwitch('s1')
    net.addLink(h1, s1)
    net.addLink(h2, s1)
    net.start()

    h1.cmd('tc qdisc add dev h1-eth0 root netem delay 10ms reorder 25% 50%')
    h1.cmd(f'ping -c 20 {h2.IP()} | grep "time=" | sed "s/.time=/" | sed "s/ ms/" > reorder.dat')

    analyze_reorder()
    net.stop()

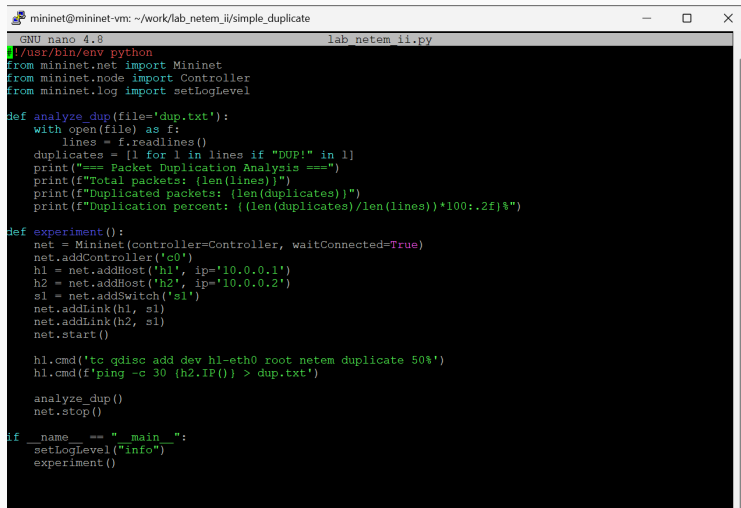
if __name__ == "__main__":
    setLogLevel("info")
    experiment()
```

Выполнение эксперимента по изменению порядка пакетов

```
mininet@mininet-vm:~/work/lab_netem_ii/delay_reorder$ nano lab_netem_ii.py
mininet@mininet-vm:~/work/lab_netem_ii/delay_reorder$ make
sudo python lab_netem_ii.py
*** Configuring hosts
h1 h2
*** Starting controller
c0
*** Starting 1 switches
s1 ...
*** Waiting for switches to connect
s1
=== Packet Reordering Analysis ===
Total packets: 20
Fast path (~no delay): 2
Slow path (~delayed): 18
Avg fast RTT: 0.060 ms
Avg slow RTT: 11.339 ms
*** Stopping 1 controllers
c0
*** Stopping 2 links
..
*** Stopping 1 switches
s1
*** Stopping 2 hosts
h1 h2
*** Done
sudo chown mininet:mininet reordero.dat
```

Рис. 22: Выполнение эксперимента по изменению порядка пакетов

Листинг программы для эксперимента по дублированию пакетов



```
mininet@mininet-vm: ~/work/lab_netem_ii/simple_duplicate
GNU nano 4.8 lab_netem_ii.py
#!/usr/bin/env python
from mininet.net import Mininet
from mininet.node import Controller
from mininet.log import setLogLevel

def analyze_dup(file='dup.txt'):
    with open(file) as f:
        lines = f.readlines()
        duplicates = [l for l in lines if "DUP!" in l]
        print("=== Packet Duplication Analysis ===")
        print(f"Total packets: {len(lines)}")
        print(f"Duplicated packets: {len(duplicates)}")
        print(f"Duplication percent: {(len(duplicates)/len(lines))*100:.2f}%")

def experiment():
    net = Mininet(controller=Controller, waitConnected=True)
    net.addController('c0')
    h1 = net.addHost('h1', ip='10.0.0.1')
    h2 = net.addHost('h2', ip='10.0.0.2')
    s1 = net.addSwitch('s1')
    net.addLink(h1, s1)
    net.addLink(h2, s1)
    net.start()

    h1.cmd('tc qdisc add dev h1-eth0 root netem duplicate 50%')
    h1.cmd(f'ping -c 30 {h2.IP()} > dup.txt')

    analyze_dup()
    net.stop()

if __name__ == "__main__":
    setLogLevel("info")
    experiment()
```

Рис. 23: Листинг программы для эксперимента по дублированию пакетов

Выполнение эксперимента по дублированию пакетов

```
mininet@mininet-vm:~/work/lab_netem_ii/simple_duplicates$ make
sudo python lab_netem_ii.py
*** Configuring hosts
h1 h2
*** Starting controller
c0
*** Starting 1 switches
s1 ...
*** Waiting for switches to connect
s1
=== Packet Duplication Analysis ===
Total packets: 49
Duplicated packets: 14
Duplication percent: 28.57%
*** Stopping 1 controllers
c0
*** Stopping 2 links
..
*** Stopping 1 switches
s1
*** Stopping 2 hosts
h1 h2
*** Done
sudo chown mininet:mininet dup.txt
```

Рис. 24: Выполнение эксперимента по дублированию пакетов

Выводы

В результате выполнения данной лабораторной работы я получил навыки проведения интерактивных экспериментов в среде Mininet по исследованию параметров сети, связанных с потерей, дублированием, изменением порядка и повреждением пакетов при передаче данных.

Список литературы

1. Mininet [Электронный ресурс]. Mininet Project Contributors. URL: <http://mini-net.org/> (дата обращения: 06.10.2025).
