

SDN-Lab3

前言

实验目的：

1. 学习利用 `ryu.topology.api` 发现网络拓扑
2. 学习利用 LLDP 和 Echo 数据包测量链路时延
3. 学习计算基于跳数和基于时延的最短路由
4. 学习设计能够容忍链路故障的路由策略
5. 分析网络集中式控制与分布式控制的差异，思考 SDN 的得与失

实验背景：

时间来到 1970 年,在你的建设下 ARPANET 飞速发展,在一年内从原来西部 4 个结点组成的简单网络逐渐发展为拥有 9 个结点,横跨东西海岸,初具规模的网络。

ARPANET 的拓展极大地便利了东西海岸之间的通信,但用户仍然十分关心网络服务的性能。一条时

延较小的转发路由将显著提升用户体验,尤其是在一些实时性要求很高的应用场景下。另外,路由策略对网络故障的容忍能力也是影响用户体验的重要因素,好的路由策略能够向用户隐藏一定程度的链路故障,使得个别链路断开后用户间的通信不至于中断。

SDN 是一种集中式控制的网络架构,控制器可以方便地获取网络拓扑、各链路和交换机的性能指标、网络故障和拓扑变化等全局信息,这也是 SDN 的优势之一。在掌握全局信息的基础上,SDN 就能实现更高效、更健壮的路由策略。

在正式任务之前,为帮助同学们理解,本指导书直接给出了一个示例。请运行示例程序,理解怎样利用 `ryu.topology.api` 获取网络拓扑,并计算 **跳数最少的路由**。

跳数最少的路由不一定是最快的路由,在实验任务一中,你将学习怎样利用 LLDP 和 Echo 数据包

测量链路时延,并计算 **时延最小的路由**。

1970 年的网络硬件发展尚不成熟,通信链路和交换机端口发生故障的概率较高。在实验任务二中,

你将学习在链路不可靠的情况下,设计 **对链路故障有一定容忍能力的路由策略**。

实验备注：

为了更加细致地展示代码分析，从这章教程开始，每一部分的实验代码将以"节选"形式展示，保留关键内容并进行分析，实验完整代码在最后的附录内：)

实验0 最少跳数路径

预备知识

用 `ryu.topology.api` 获取网络拓扑,并计算 跳数最少的路由

拓扑感知：

控制器首先要获取网络的拓扑结构,才能够对网络进行各种测量分析,网络拓扑主要包括主机、链路和交换机的相关信息

链路发现原理：

LLDP(Link Layer Discover Protocol) 即链路层发现协议,Ryu 主要利用 LLDP 发现网络拓扑。LLDP 被封装在以太网帧中,结构如下图：

Preamble	Dst MAC	Src MAC	Ether- type: 0x88CC	Chassis ID TLV	Port ID TLV	Time to live TLV	Opt. TLVs	End of LLDPDU TLV	Frame check seq.
----------	------------	------------	---------------------------	----------------------	-------------------	---------------------------	--------------	-------------------------	------------------------

其中深灰色的即为 LLDP 负载,Chassis ID TLV , Port ID TLV 和 Time to live TLV 是三个强制字段,分别代表交换机标识符(在局域网中是独一无二的),端口号和 TTL

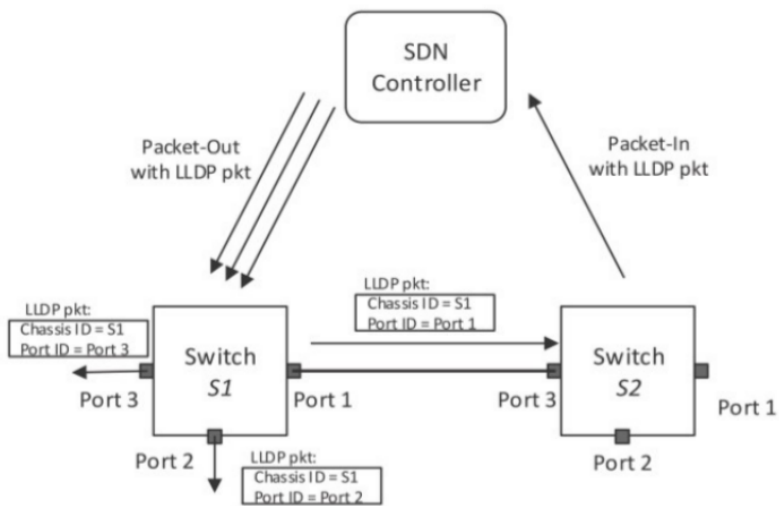
Ryu 如何利用 LLDP 发现链路：(假设有两个OpenFlow交换机连接在控制器上)

1. SDN 控制器构造 `PacketOut` 消息向 S1 的三个端口分别发送 LLDP 数据包,其中将 Chassis ID TLV 和 Port ID TLV 分别置为 S1 的 `dpid` 和端口号;
2. 控制器向交换机 S1 中下发流表,流表规则为: 将从 Controller 端口收到的 LLDP 数据包从他的对应端口发送出去;
3. 控制器向交换机 S2 中下发流表,流表规则为: 将从非 Controller 接收到的 LLDP 数据包发送给控制器;
4. 控制器通过解析 LLDP 数据包,得到链路的源交换机,源接口,通过收到的 `PacketIn` 消息知道目的交换机和目的接口。

沉默主机现象：

主机如果没有主动发送过数据包,控制器就无法发现主机。运行前面的 `NetworkAwareness.py` 时,你可能会看到 `host` 输出为空,这就是沉默主机现象导致的。

你可以在 `mininet` 中运行 `pingall` 指令,令每个主机发出 ICMP 数据包,这样控制器就能够发现主机。当然命令的结果是 `ping` 不通,因为程序中并没有下发路由的代码



实验代码

```
# NetworkAwareness.py (offered by TA as a reference)
from ryu.base import app_manager
from ryu.ofproto import ofproto_v1_3
from ryu.controller.handler import set_ev_cls
from ryu.controller.handler import MAIN_DISPATCHER, CONFIG_DISPATCHER
from ryu.controller import ofp_event
from ryu.lib.packet import packet
from ryu.lib.packet import ethernet
from ryu.lib import hub
from ryu.topology.api import get_all_host, get_all_link, get_all_switch

class NetworkAwareness(app_manager.RyuApp):
    OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]

    def __init__(self, *args, **kwargs):
        super(NetworkAwareness, self).__init__(*args, **kwargs)
        self.dpid_mac_port = {}
        self.topo_thread = hub.spawn(self._get_topology)

    def add_flow(self, datapath, priority, match, actions):
        dp = datapath
        ofp = dp.ofproto
        parser = dp.ofproto_parser

        inst = [parser.OFPInstructionActions(ofp.OFPIT_APPLY_ACTIONS, actions)]
        mod = parser.OFPFlowMod(datapath=dp, priority=priority, match=match,
                                dp.send_msg(mod))
```

```

@set_ev_cls(ofp_event.EventOFPSwitchFeatures, CONFIG_DISPATCHER)
def switch_features_handler(self, ev):
    msg = ev.msg
    dp = msg.datapath
    ofp = dp.ofproto
    parser = dp.ofproto_parser
    match = parser.OFPMatch()
    actions = [parser.OFPActionOutput(ofp.OFPP_CONTROLLER, ofp.OFPCML_NO_
self.add_flow(dp, 0, match, actions)

def _get_topology(self):
    while True:
        self.logger.info('\n\n\n')

        hosts = get_all_host(self)
        switches = get_all_switch(self)
        links = get_all_link(self)

        self.logger.info('hosts:')
        for hosts in hosts:
            self.logger.info(hosts.to_dict())

        self.logger.info('switches:')
        for switch in switches:
            self.logger.info(switch.to_dict())

        self.logger.info('links:')
        for link in links:
            self.logger.info(link.to_dict())

        hub.sleep(2)

```

实验1 链路时延测量

预备知识

链路时延计算：

控制器将带有时间戳的 LLDP 报文下发给 S1，S1 转发给 S2，S2 上传回控制器(即内圈红色箭头的路径)，根据收到的时间和发送时间即可计算出控制器经 S1 到 S2 再返回控制器的时延，记为

lldp_delay_s12

反之,控制器经 S2 到 S1 再返回控制器的时延,记为 `lldp_delay_s21`
交换机收到控制器发来的Echo报文后会立即回复控制器,我们可以利用 Echo Request/Reply 报文求出控制器到 S1 、 S2 的往返时延,记为 `echo_delay_s1` , `echo_delay_s2`

则 S1 到 S2 的时延:

$$delay = (lldp_delay_s12 + lldp_delay_s21 - echo_delay_s1 - echo_delay_s2)$$

修改Ryu源码并编译

1. ryu/topology/Switches.py 的 PortData/init():

PortData 记录交换机的端口信息, 我们需要增加 `self.delay` 属性记录上述的 `lldp_delay`
`self.timestamp` 为 LLDP 包在发送时被打上的时间戳

```
class PortData(object):
    def __init__(self, is_down, lldp_data):
        super(PortData, self).__init__()
        self.is_down = is_down
        self.lldp_data = lldp_data
        self.timestamp = None
        self.sent = 0
        self.delay = 0
```

2. ryu/topology/Switches/lldp_packet_in_handler():

`lldp_packet_in_handler()` 处理接收到的 LLDP 包, 在这里用收到 LLDP 报文的时间戳减去发送时的时间戳即为 `lldp_delay`, 由于 LLDP 报文被设计为经一跳后转给控制器, 我们可将 `lldp_delay` 存入发送 LLDP 包对应的交换机端口

```
@set_ev_cls(ofp_event.EventOFPPacketIn, MAIN_DISPATCHER)
def lldp_packet_in_handler(self, ev):
    # add receive timestamp
    recv_timestamp = time.time()
    if not self.link_discovery:
        return
    msg = ev.msg
    try:
        src_dp_id, src_port_no = LLDPpacket.lldp_parse(msg.data)
    except LLDPpacket.LLDPUnknownFormat:
        # This handler can receive all the packets which can be
```

```

        # not-LLDP packet. Ignore it silently
        return
    # calc the delay of lldp packet
    for port, port_data in self.ports.items():
        if src_dpid == port.dpid and src_port_no == port.port_no:
            send_timestamp = port_data.timestamp
            if send_timestamp:
                port_data.delay = rcv_timestamp - send_timestamp

```

测量 LLDP Delay

1. add: `self.lldp_delay = {}` in `__init__(...)`

```

def __init__(self, *args, **kwargs):
    super(NetworkAwareness, self).__init__(*args, **kwargs)
    # basic config info of a topo
    self.switch_info = {} # dpid: datapath
    self.link_info = {} # (s1, s2): s1.port
    self.port_link={} # s1,port:s1,s2
    self.port_info = {} # dpid: (ports linked hosts)
    self.topo_map = nx.Graph()
    self.topo_thread = hub.spawn(self._get_topology)
    self.lldp_delay = {}
    self.delay = {}
    self.controller_switch_delay = {}

    # define weight of path
    self.weight = 'hop' # use "hopNumber between 2 nodes" as weight in St
    self.switches = None

```

2. add `packet_in_handler(...)`

```

def packet_in_handler(self, ev):
    msg = ev.msg
    dp = msg.datapath
    ofp = dp.ofproto
    parser = dp.ofproto_parser
    dpid = dp.id

    pkt = packet.Packet(msg.data)
    eth_pkt = pkt.get_protocol(ethernet.ethernet)
    arp_pkt = pkt.get_protocol(arp.arp)
    pkt_type = eth_pkt.ethertype

```

```

if pkt_type == ether_types.ETH_TYPE_LLDP:
    src_dpid, src_port_no = LLDPpacket.lldp_parse(msg.data)
    if self.switches is None:
        self.switches = lookup_service_brick('switches')

    for port in self.switches.ports.keys():
        if src_dpid == port.dpid and src_port_no == port.port_no:
            self.lldp_delay[(src_dpid,dpid)] = self.switches.ports[port].

```

测量 ECHO Delay

让控制器给交换机发送 ECHO request 消息，然后再让交换机返回给控制器，通过两个时间戳来
得到 ECHO 时间，同时这里时间差也乘以 1000，保证与上述单位一致

```

@set_ev_cls(ofp_event.EventOFPEchoReply, [MAIN_DISPATCHER, CONFIG_DISPATCHER, ...])
def echo_reply_handler(self, ev):
    now_timestamp = time.time()
    try:
        echo_delay = now_timestamp - eval(ev.msg.data)
        self.controller_switch_delay[ev.msg.datapath.id] = echo_delay * 1
    except:
        print ("Overtime! Error!")
        return

def send_echo_request(self, switch):
    datapath = switch.dp
    parser = datapath.ofproto_parser
    echo_req = parser.OFPEchoRequest(datapath, data=bytes("%.12f"%time.time))
    datapath.send_msg(echo_req)

```

计算总时延

特殊情况分析：

以下是计算总时延的代码，_get_topology() 函数本身是一个不断运行的线程，所以我们在
这里获取时延，来得到不断的时延更新。

值得注意的是，这里计算 echo_request 的过程中需要取"冷却时间"来暂停一下，如果不暂停的话，echo delay 非常大，不符合运转过程(这里我取的是 hub.sleep(0.5))。

猜测原因是：如果快速给每个交换机发送 echo_request，每个交换机会同时快速发送 echo_reply 到控制器，而控制器没办法一下子同时处理，则产生排队时延

因此：会降低ofp_event.EventOFPEchoReply 的处理速度,导致测量误差非常大

测量并计算总时延代码：

```
def _get_topology(self):
    _hosts, _switches, _links = None, None, None
    while True:
        hosts = get_host(self)
        switches = get_switch(self)
        links = get_link(self)

        # If topo is still, continue
        if [str(x) for x in hosts] == _hosts and [str(x) for x in switches] == _switches:
            continue

        # update topo_map when topology change
        _hosts, _switches, _links = [str(x) for x in hosts], [str(x) for x in switches], [str(x) for x in links]

        for switch in switches: # ports & Sw.
            self.port_info.setdefault(switch.dp.id, set()) # origin, a Sw. wi
            # record all ports in this Sw.
            for port in switch.ports:
                self.port_info[switch.dp.id].add(port.port_no) # attach ports
            self.send_echo_request(switch)
            hub.sleep(0.5)

        for host in hosts: # Sw. & hosts
            # take one ipv4 address as host id
            if host.ipv4:
                self.link_info[(host.port.dpid, host.ipv4[0])] = host.port.port_no
                self.topo_map.add_edge(host.ipv4[0], host.port.dpid, hop=1, cost=1)

        for link in links:
            # delete link (host-port -- link -- host-port)
            self.port_info[link.src.dpid].discard(link.src.port_no)
            self.port_info[link.dst.dpid].discard(link.dst.port_no)

            # s1 -> s2: s1.port, s2 -> s1: s2.port
            self.port_link[(link.src.dpid, link.src.port_no)] = (link.src.dpid, link.src.port_no)
            self.port_link[(link.dst.dpid, link.dst.port_no)] = (link.dst.dpid, link.dst.port_no)

            self.link_info[(link.src.dpid, link.dst.dpid)] = link.src.port_no
            self.link_info[(link.dst.dpid, link.src.dpid)] = link.dst.port_no
            # self.topo_map.add_edge(link.src.dpid, link.dst.dpid, hop=1, is_bidirectional=True)

        delay_src_to_dst = 0.0
```



```

delay_dst_to_src = 0.0
delay_ctl_to_src = 0.0
delay_ctl_to_dst = 0.0

if (link.src.dpid, link.dst.dpid) in self.lldp_delay:
    delay_src_to_dst = self.lldp_delay[(link.src.dpid, link.dst.c

if (link.dst.dpid, link.src.dpid) in self.lldp_delay:
    delay_dst_to_src = self.lldp_delay[(link.dst.dpid, link.src.c

if link.src.dpid in self.controller_switch_delay:
    delay_ctl_to_src = self.controller_switch_delay[link.src.dpic

if link.dst.dpid in self.controller_switch_delay:
    delay_ctl_to_dst = self.controller_switch_delay[link.dst.dpic

delay = (delay_src_to_dst + delay_dst_to_src +
        delay_ctl_to_src + delay_ctl_to_dst) / 2

if (delay < 0):
    delay = 0

self.delay[(link.src.dpid, link.dst.dpid)] = delay
self.topo_map.add_edge(link.src.dpid, link.dst.dpid, hop = 1, del

if self.weight == 'hop':
    self.show_topo_map_1()
if self.weight == 'delay':
    self.show_topo_map_2()

hub.sleep(GET_TOPOLOGY_INTERVAL)

```

这里如果计算出 `delay<0` 时,让 `delay` 为 `0`。

BUT! 经过多次实验,发现不存在 `delay<0` 的情况, 有理由怀疑是上述情况导致的?

实验结果与验证

实际延迟测量

```

topo map:
  node      ->      node      delay
    1                9        10.6ms
    2                3        11.5ms
    2                4        13.5ms
    3                4        14.5ms
    4                5        15.6ms
    5                9        29.5ms
    5                6        18.0ms
    6                7        10.6ms
    7                8        62.6ms
    8                9        17.6ms

```

理论设置

```

59      # add edges between switches
60      self.addLink( s1 , s9, bw=10, delay='10ms')
61      self.addLink( s2 , s3, bw=10, delay='11ms')
62      self.addLink( s2 , s4, bw=10, delay='13ms')
63      self.addLink( s3 , s4, bw=10, delay='14ms')
64      self.addLink( s4 , s5, bw=10, delay='15ms')
65      self.addLink( s5 , s9, bw=10, delay='29ms')
66      self.addLink( s5 , s6, bw=10, delay='17ms')
67      self.addLink( s6 , s7, bw=10, delay='10ms')
68      self.addLink( s7 , s8, bw=10, delay='62ms')
69      self.addLink( s8 , s9, bw=10, delay='17ms')
70

```

该权重选择下的链路选择

```

*** Starting CLI:
mininet> SDC ping -i 0.5 MIT
PING 10.0.0.3 (10.0.0.3) 56(84) bytes of data.
64 bytes from 10.0.0.3: icmp_seq=10 ttl=64 time=69.9 ms
64 bytes from 10.0.0.3: icmp_seq=11 ttl=64 time=127 ms
64 bytes from 10.0.0.3: icmp_seq=12 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=13 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=14 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=15 ttl=64 time=126 ms
^C
--- 10.0.0.3 ping statistics ---
15 packets transmitted, 6 received, 60% packet loss, time 7106ms
rtt min/avg/max/mdev = 69.951/117.051/127.727/21.075 ms
mininet>

```

```

path: 10.0.0.5 -> 10.0.0.3
10.0.0.5 -> 1:s6:2 -> 4:s5:3 -> 3:s9:4 -> 3:s8:1 -> 10.0.0.3    delay=64.7ms
topo map:
  node      ->      node      delay
    1                9        10.5ms
    2                3        11.6ms
    2                4        13.6ms
    3                4        14.6ms
    4                5        16.0ms
    5                9        29.7ms
    5                6        17.6ms
    6                10.0.0.5    0.0ms
    6                7         10.5ms
    7                8         62.8ms
    8                9         17.4ms
    8                10.0.0.3    0.0ms

```

实验2：容忍链路故障

实验背景

1970年的网络硬件发展尚不成熟,通信链路和交换机端口发生故障的概率较高。请设计 **Ryu app** ,在任务一的基础上实现容忍链路故障的路由选择:每当链路出现故障时,重新选择当前可用路径中时延最低的路径;当链路故障恢复后,也重新选择新的时延最低的路径。

请在实验报告里附上你计算的:

(1)最小时延路径 (2)最小时延路径的 RTT (3)链路故障/恢复后发生的路由转移

模拟链路故障:

```
mininet>link s1 s4 down
mininet>link s1 s4 up
```

控制器捕捉链路故障:

链路状态改变时,链路关联的端口状态也会变化,从而产生端口状态改变的事件,即 **EventOFPPortStatus**, 通过将此事件与你设计的处理函数绑定在一起,就可以获取状态改变的信息,执行相应的处理。可以在你的代码中实现你需要的 **EventOFPPortStatus** 事件处理函数。

OFPPFC_DELETE 消息:

与向交换机中增加流表的 **OFPPFC_ADD** 命令不同, **OFPPFC_DELETE** 消息用于删除交换机中符合匹配项的所有流表。

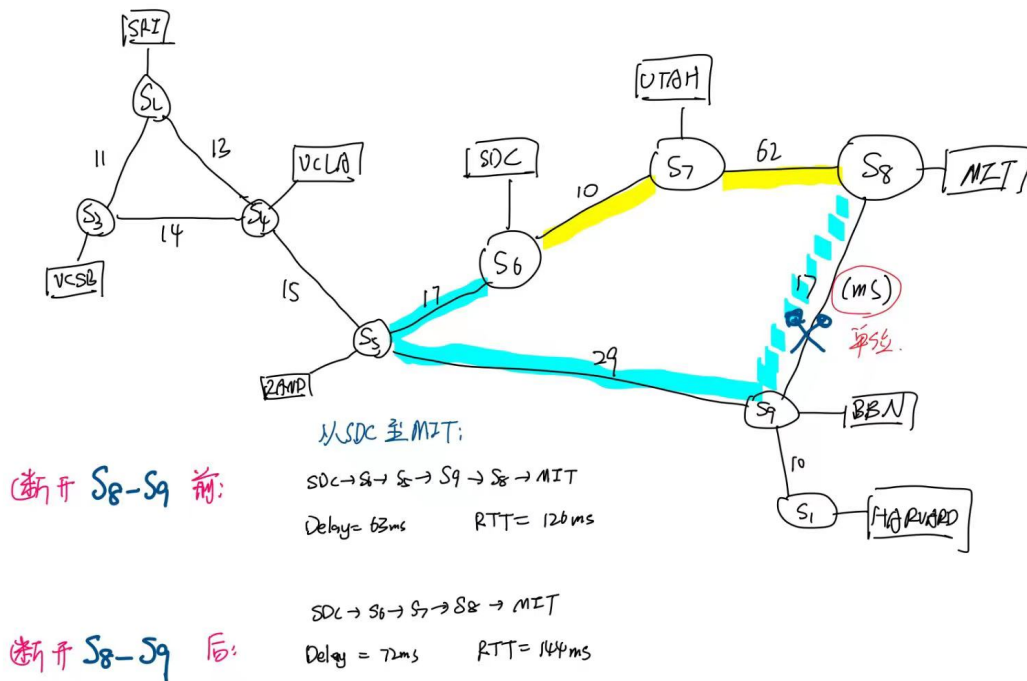
由于添加和删除都属于 **OFPFFlowMod** 消息,因此只需稍微修改 **add_flow()** 函数,即可生成 **delete_flow()** 函数。

Packet_In 消息的合理利用:

基本思路是:在链路发生改变时,删除受影响的链路上所有交换机上的相关流表的信息,下一次交换机将匹配默认流表项,向控制器发送 **packet_in** 消息,控制器重新计算并下发最小时延路径。

理论分析

对于原拓扑:考察断开S8-S9后的情景



代码设计

OFPPC_DELETE: 几乎跟 add_flow() 一模一样, 略之!

```
def delete_flow(self, datapath, match):
    # get this on line
    dp = datapath
    ofp = dp.ofproto
    parser = dp.ofproto_parser
    inst = []

    req = parser.OFPFlowMod (
        dp,
        0, 0, 0, ofp.OFPFC_DELETE,
        0, 0, 0, ofp.OFP_NO_BUFFER,
        ofp.OFPP_ANY,
        ofp.OFPG_ANY,
        ofp.OFPFF_SEND_FLOW_REM,
        match,
        inst
    )
    dp.send_msg(req)
```

链路断裂带来的主机/交换机行为:

```

@set_ev_cls(ofp_event.EventOFPPortStatus, MAIN_DISPATCHER)
def port_status_handler(self, ev):
    msg = ev.msg
    datapath = ev.datapath
    ofproto = ev.ofproto
    parser = datapath.ofproto_parser

    if msg.reason in [ofproto.OFPPR_ADD, ofproto.OFPPR_MODIFY]:
        datapath.ports[msg.desc.port_no] = msg.desc
        self.topo_map.clear()

        for dpid in self.port_info.keys():
            for port in self.port_info[dpid]:
                match = parser.OFPMatch(in_port = port)
                self.delete_flow(self.switch_info[dpid], match)
    elif msg.reason == ofproto.OFPPR_DELETE:
        datapath.ports.pop(msg.desc.port_no, None)
    else:
        return

self.send_event_to_observers(ofp_event.EventOFPPortStateChange(datapath, msg.r

```

解释：这是删除所有交换机连向的主机端口，让主机下次 ping 必定触发 Packetin 消息。下一次交换机将匹配默认流表项(prio=0)，向控制器发送 packet_in 消息，控制器重新计算并下发最小时延路径

实验结果与验证

在上述理论分析的拓扑中，考察SDC到MIT，故障情景同上

初始正常链路

```

ms delay)
BBN BBN-eth0:s9-eth1
HARVARD HARVARD-eth0:s1-eth1
MIT MIT-eth0:s8-eth1
RAND RAND-eth0:s5-eth1
SDC SDC-eth0:s6-eth1
SRI SRI-eth0:s2-eth1
UCLA UCLA-eth0:s4-eth1
UCSB UCSB-eth0:s3-eth1
UTAH UTAH-eth0:s7-eth1
*** Starting CLI:
mininet> SDC ping MIT
PING 10.0.0.3 (10.0.0.3) 56(84) bytes of data.
64 bytes from 10.0.0.3: icmp_seq=5 ttl=64 time=70.7 ms
64 bytes from 10.0.0.3: icmp_seq=6 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=7 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=8 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=9 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=10 ttl=64 time=126 ms
^C
--- 10.0.0.3 ping statistics ---
10 packets transmitted, 6 received, 40% packet loss, time 9077ms
rtt min/avg/max/mdev = 70.712/117.104/126.642/20.749 ms
mininet>

```

```

path: 10.0.0.5 -> 10.0.0.3
10.0.0.5 -> 1:s6:2 -> 4:s5:3 -> 3:s9:4 -> 3:s8:1 -> 10.0.0.3    delay=64.7ms

```

RTT = 126ms，路径跟理论分析的也一样

故障发生后调整链路

```

mininet> link s8 s9 down
mininet> SDC ping MIT
PING 10.0.0.3 (10.0.0.3) 56(84) bytes of data.
64 bytes from 10.0.0.3: icmp_seq=2 ttl=64 time=76.6 ms
64 bytes from 10.0.0.3: icmp_seq=3 ttl=64 time=144 ms
64 bytes from 10.0.0.3: icmp_seq=4 ttl=64 time=144 ms
64 bytes from 10.0.0.3: icmp_seq=5 ttl=64 time=144 ms
64 bytes from 10.0.0.3: icmp_seq=6 ttl=64 time=144 ms
^C
--- 10.0.0.3 ping statistics ---
6 packets transmitted, 5 received, 16% packet loss, time 5026ms
rtt min/avg/max/mdev = 76.623/130.791/144.471/27.085 ms
mininet>

```

```

path: 10.0.0.5 -> 10.0.0.3
10.0.0.5 -> 1:s6:3 -> 2:s7:3 -> 2:s8:1 -> 10.0.0.3    delay=73.3ms

```

RTT = 144ms，路径跟理论分析的也一样

故障恢复后的链路

```

mininet> link s8 s9 up
mininet> SDC ping MIT
PING 10.0.0.3 (10.0.0.3) 56(84) bytes of data.
64 bytes from 10.0.0.3: icmp_seq=4 ttl=64 time=70.7 ms
64 bytes from 10.0.0.3: icmp_seq=5 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=6 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=7 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=8 ttl=64 time=126 ms
64 bytes from 10.0.0.3: icmp_seq=9 ttl=64 time=126 ms
^C
--- 10.0.0.3 ping statistics ---

```

```

path: 10.0.0.5 -> 10.0.0.3
10.0.0.5 -> 1:s6:2 -> 4:s5:3 -> 3:s9:4 -> 3:s8:1 -> 10.0.0.3    delay=64.4ms

```

RTT = 126ms, 路径跟故障发生前一样, 说明恢复成功

附录

network_awareness.py

```

from ryu.base import app_manager
from ryu.base.app_manager import lookup_service_brick
from ryu.ofproto import ofproto_v1_3
from ryu.controller.handler import set_ev_cls
from ryu.controller.handler import MAIN_DISPATCHER, CONFIG_DISPATCHER, DEAD_C
from ryu.controller import ofp_event
from ryu.lib.packet import packet
from ryu.lib.packet import ethernet, arp
from ryu.lib.packet import ether_types
from ryu.lib import hub
from ryu.topology import event
from ryu.topology.api import get_host, get_link, get_switch
from ryu.topology.switches import LLDPPacket

import networkx as nx
import copy
import time

# this script is to get network topology by controller
# with the help of Ryu
# method:
...
    sudo mn --topo=tree,2,2 --controller remote
    ryu-manager NetworkAwareness.py --observe-links
...

GET_TOPOLOGY_INTERVAL = 2
SEND_ECHO_REQUEST_INTERVAL = 0.05

```



```
GET_DELAY_INTERVAL = 2
```

```
class NetworkAwareness(app_manager.RyuApp):
```

```
    OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]
```

```
    def __init__(self, *args, **kwargs):
```

```
        super(NetworkAwareness, self).__init__(*args, **kwargs)
```

```
        # basic config info of a topo
```

```
        self.switch_info = {} # dpid: datapath
```

```
        self.link_info = {} # (s1, s2): s1.port
```

```
        self.port_link={} # s1,port:s1,s2
```

```
        self.port_info = {} # dpid: (ports linked hosts)
```

```
        self.topo_map = nx.Graph()
```

```
        self.topo_thread = hub.spawn(self._get_topology)
```

```
        self.lldp_delay = {}
```

```
        self.delay = {}
```

```
        self.controller_switch_delay = {}
```

```
        # define weight of path
```

```
        self.weight = 'hop' # use "hopNumber between 2 nodes" as weight in S
```

```
        self.switches = None
```

```
    def add_flow(self, datapath, priority, match, actions):
```

```
        # add an object to flow_table
```

```
        dp = datapath # Sw.
```

```
        ofp = dp.ofproto # objects and consts about OpenFlow itself
```

```
        parser = dp.ofproto_parser # parser of OpenFlow
```

```
        inst = [parser.OFPInstructionActions(ofp.OFPIT_APPLY_ACTIONS, actions
```

```
        # message downing
```

```
        mod = parser.OFPFlowMod(datapath=dp, priority=priority, match=match,
```

```
        ...
```

```
        mod = message downing to Sw.
```

```
        dp = Sw.
```

```
        prio = the processing Prio.
```

```
        match = matching condition
```

```
        inst = corresponding actions
```

```
        ...
```

```
        dp.send_msg(mod)
```

```
    def delete_flow(self, datapath, match):
```

```
        # get this on line
```

```
        dp = datapath
```

```
        ofp = dp.ofproto
```

```
        parser = dp.ofproto_parser
```



```

inst = []

req = parser.OFPFlowMod (
    dp,
    0, 0, 0, ofp.OFPFC_DELETE,
    0, 0, 0, ofp.OFP_NO_BUFFER,
    ofp.OFPP_ANY,
    ofp.OFPG_ANY,
    ofp.OFPFF_SEND_FLOW_REM,
    match,
    inst
)
dp.send_msg(req)

```

```

@set_ev_cls(ofp_event.EventOFPSwitchFeatures, CONFIG_DISPATCHER)
def switch_features_handler(self, ev):
    # 在交换机连接时向其添加一个默认的流表项，使所有未匹配到的流量都发送到控制器
    msg = ev.msg # message of packet
    dp = msg.datapath # Sw.
    ofp = dp.ofproto
    parser = dp.ofproto_parser

    match = parser.OFPMatch() # MatchObject = None, matching all flows
    actions = [parser.OFPActionOutput(ofp.OFPP_CONTROLLER, ofp.OFPCML_NO_
    ...

    ofp.OFPP_CONTROLLER: Controller Receiving Port
    ofp.OFPCML_NO_BUFFER: no Buffer for this msg
    ...

    self.add_flow(dp, 0, match, actions) # matching all, so prio = 0

@set_ev_cls(ofp_event.EventOFPPortStatus, MAIN_DISPATCHER)
def port_status_handler(self, ev):
    msg = ev.msg
    datapath = ev.datapath
    ofproto = ev.ofproto
    parser = datapath.ofproto_parser

    if msg.reason in [ofproto.OFPPR_ADD, ofproto.OFPPR_MODIFY]:
        datapath.ports[msg.desc.port_no] = msg.desc
        self.topo_map.clear()

        for dpid in self.port_info.keys():
            for port in self.port_info[dpid]:
                match = parser.OFPMatch(in_port = port)
                self.delete_flow(self.switch_info[dpid], match)
    elif msg.reason == ofproto.OFPPR_DELETE:

```

```

        datapath.ports.pop(msg.desc.port_no, None)
    else:
        return

    self.send_event_to_observers(ofp_event.EventOFPPortStateChange(datapath

@set_ev_cls(ofp_event.EventOFPSwitchChange, [MAIN_DISPATCHER, DEAD_DISPATCHER])
def state_change_handler(self, ev):
    # 当交换机状态改变时（连接或断开），会触发该方法：处理交换机连接和断开事件，更新内部
    dp = ev.datapath # Sw.
    dpid = dp.id # Sw.ID

    if ev.state == MAIN_DISPATCHER: # Sw. is in connection (ON)
        self.switch_info[dpid] = dp # add map<ID, Sw.>

    if ev.state == DEAD_DISPATCHER: # Sw. is out of connection (OFF)
        del self.switch_info[dpid] # del ...

@set_ev_cls(ofp_event.EventOFPErrorReply, [MAIN_DISPATCHER, CONFIG_DISPATCHER])
def error_reply_handler(self, ev):
    now_timestamp = time.time()
    try:
        echo_delay = now_timestamp - eval(ev.msg.data)
        self.controller_switch_delay[ev.msg.datapath.id] = echo_delay * 1
    except:
        print ("Overtime! Error!")
        return

def send_echo_request(self, switch):
    datapath = switch.dp
    parser = datapath.ofproto_parser
    echo_req = parser.OFPErrorRequest(datapath, data=bytes("%.12f"%time.time))
    datapath.send_msg(echo_req)

@set_ev_cls(ofp_event.EventOFPErrorReply, MAIN_DISPATCHER)
def error_reply_handler(self, ev):
    msg = ev.msg
    dp = msg.datapath
    ofp = dp.ofproto
    parser = dp.ofproto_parser
    dpid = dp.id

    pkt = packet.Packet(msg.data)
    eth_pkt = pkt.get_protocol(ethernet.ethernet)
    arp_pkt = pkt.get_protocol(arp.arp)
    pkt_type = eth_pkt.ethertype

```

```

if pkt_type == ether_types.ETH_TYPE_LLDP:
    src_dpid, src_port_no = LLDPpacket.lldp_parse(msg.data)
    if self.switches is None:
        self.switches = lookup_service_brick('switches')

    for port in self.switches.ports.keys():
        if src_dpid == port.dpid and src_port_no == port.port_no:
            self.lldp_delay[(src_dpid,dpid)] = self.switches.ports[port]

def _get_topology(self):
    _hosts, _switches, _links = None, None, None
    while True:
        hosts = get_host(self)
        switches = get_switch(self)
        links = get_link(self)

        # If topo is still, continue
        if [str(x) for x in hosts] == _hosts and [str(x) for x in switches] == _switches:
            continue

        # update topo_map when topology change
        _hosts, _switches, _links = [str(x) for x in hosts], [str(x) for x in switches], [str(x) for x in links]

        for switch in switches: # ports & Sw.
            self.port_info.setdefault(switch.dpid, set()) # origin, a Sw.
            # record all ports in this Sw.
            for port in switch.ports:
                self.port_info[switch.dpid].add(port.port_no) # attach port
            self.send_echo_request(switch)
            hub.sleep(0.5)

        for host in hosts: # Sw. & hosts
            # take one ipv4 address as host id
            if host.ipv4:
                self.link_info[(host.dpid, host.ipv4[0])] = host.port
                self.topo_map.add_edge(host.ipv4[0], host.dpid, hop=1)

        for link in links:
            # delete link (host-port -- link -- host-port)
            self.port_info[link.src.dpid].discard(link.src.port_no)
            self.port_info[link.dst.dpid].discard(link.dst.port_no)

            # s1 -> s2: s1.port, s2 -> s1: s2.port
            self.port_link[(link.src.dpid,link.src.port_no)]=(link.src.dpid,link.dst.port_no)
            self.port_link[(link.dst.dpid,link.dst.port_no)] = (link.dst.dpid,link.src.port_no)

```

```

self.link_info[(link.src.dpid, link.dst.dpid)] = link.src.port
self.link_info[(link.dst.dpid, link.src.dpid)] = link.dst.port
# self.topo_map.add_edge(link.src.dpid, link.dst.dpid, hop=1,

delay_src_to_dst = 0.0
delay_dst_to_src = 0.0
delay_ctl_to_src = 0.0
delay_ctl_to_dst = 0.0

if (link.src.dpid, link.dst.dpid) in self.lldp_delay:
    delay_src_to_dst = self.lldp_delay[(link.src.dpid, link.s

if (link.dst.dpid, link.src.dpid) in self.lldp_delay:
    delay_dst_to_src = self.lldp_delay[(link.dst.dpid, link.s

if link.src.dpid in self.controller_switch_delay:
    delay_ctl_to_src = self.controller_switch_delay[link.src.

if link.dst.dpid in self.controller_switch_delay:
    delay_ctl_to_dst = self.controller_switch_delay[link.dst.

delay = (delay_src_to_dst + delay_dst_to_src +
        delay_ctl_to_src + delay_ctl_to_dst) / 2

if (delay < 0):
    delay = 0

self.delay[(link.src.dpid, link.dst.dpid)] = delay
self.topo_map.add_edge(link.src.dpid, link.dst.dpid, hop = 1,

if self.weight == 'hop':
    self.show_topo_map_1()
if self.weight == 'delay':
    self.show_topo_map_2()

hub.sleep(GET_TOPOLOGY_INTERVAL)

def shortest_path(self, src, dst, weight='hop'):
    try:
        # import nx to solve "shortest path" automatically
        paths = list(nx.shortest_simple_paths(self.topo_map, src, dst, we
        return paths[0]
    except:
        self.logger.info('host not find/no path')

```

```

def show_topo_map_1(self):
    self.logger.info('topo map:')
    self.logger.info('{:^10s} -> {:^10s} {}'.format('node', 'node', 'hop'))
    for src, dst in self.topo_map.edges:
        self.logger.info('{:^10s} {:^10s} {}'.format(str(src),
            str(dst), self.topo_map.edges[src, dst]['hop']))

    self.logger.info('\n')

def show_topo_map_2(self):
    self.logger.info('topo map:')
    self.logger.info('{:^10s} -> {:^10s} {}'.format('node', 'node', 'delay'))
    for src, dst in self.topo_map.edges:
        self.logger.info('{:^10s} {:^10s} '.format(str(src),
            str(dst)) + '%.1f'%self.topo_map.edges[src, dst]['delay'] + 'ms')
    self.logger.info('\n')

```

shortest_forward.py

```

# ryu-manager shortest_forward.py --observe-links
from ryu.base import app_manager
from ryu.base.app_manager import lookup_service_brick
from ryu.controller import ofp_event
from ryu.controller.handler import CONFIG_DISPATCHER, MAIN_DISPATCHER, DEAD_C
from ryu.controller.handler import set_ev_cls
from ryu.controller.handler import set_ev_cls
from ryu.ofproto import ofproto_v1_3
from ryu.lib.packet import packet
from ryu.lib.packet import ethernet, arp, ipv4
from ryu.lib.packet import ether_types
from ryu.controller import ofp_event
from ryu.topology import event
from ryu.topology.api import get_switch
import sys
from network_awareness1 import NetworkAwareness
import networkx as nx
ETHERNET = ethernet.ethernet.__name__

ETHERNET_MULTICAST = "ff:ff:ff:ff:ff:ff"
ARP = arp.arp.__name__
class ShortestForward(app_manager.RyuApp):
    OFP_VERSIONS = [ofproto_v1_3.OFP_VERSION]
    _CONTEXTS = {'network_awareness1': NetworkAwareness}

```

```

def __init__(self, *args, **kwargs):
    super(ShortestForward, self).__init__(*args, **kwargs)
    self.network_awareness1 = kwargs['network_awareness1']
    self.weight = 'delay'
    self.mac_to_port = {}
    self.sw = {}
    self.path=None
    self.switches = None
    self.ip_to_mac = {}
    self.mac_to_dpid = {}
    self.dpid_to_dp = {}
    self.ip_to_port = {}

def add_flow(self, datapath, priority, match, actions, idle_timeout=0, ha
dp = datapath
ofp = dp.ofproto
parser = dp.ofproto_parser

inst = [parser.OFPInstructionActions(ofp.OFPIT_APPLY_ACTIONS, actions
mod = parser.OFPFlowMod(
datapath=dp, priority=priority,
idle_timeout=idle_timeout,
hard_timeout=hard_timeout,
match=match, instructions=inst)
dp.send_msg(mod)

@set_ev_cls(ofp_event.EventOFPPacketIn, MAIN_DISPATCHER)
def packet_in_handler(self, ev):
    msg = ev.msg
    dp = msg.datapath
    ofp = dp.ofproto
    parser = dp.ofproto_parser

    dpid = dp.id
    in_port = msg.match['in_port']

    pkt = packet.Packet(msg.data)
    eth_pkt = pkt.get_protocol(ethernet.ethernet)
    arp_pkt = pkt.get_protocol(arp.arp)
    ipv4_pkt = pkt.get_protocol(ipv4.ipv4)
    pkt_type = eth_pkt.ethertype

    # layer 2 self-learning
    dst_mac = eth_pkt.dst
    src_mac = eth_pkt.src

```

```

    if isinstance(arp_pkt, arp.arp):
        self.handle_arp(msg, in_port, dst_mac,src_mac, pkt, pkt_type)

    if isinstance(ipv4_pkt, ipv4.ipv4):
        self.handle_ipv4(msg, ipv4_pkt.src, ipv4_pkt.dst, pkt_type)

def handle_arp(self, msg, in_port, dst,src, pkt,pkt_type):
    datapath = msg.datapath
    dpid = datapath.id
    ofp = datapath.ofproto
    parser = datapath.ofproto_parser
    arp_pkg=pkt.get_protocol(arp.arp)
    if arp_pkg.opcode == arp.ARP_REQUEST:
        if arp_pkg.src_ip not in self.ip_to_mac:
            self.ip_to_mac[arp_pkg.src_ip]=src
            self.mac_to_dpid[src]=(dpid,in_port)
            self.ip_to_port[arp_pkg.src_ip]=(dpid,in_port)
        if arp_pkg.dst_ip in self.ip_to_mac:
            self.arpReply(datapath=datapath,port=in_port,src_mac=self.ip_
                dst_mac=src,src_ip=arp_pkg.dst_ip,dst_ip=arp_pkg.src_ip)
        else:
            out_port=ofp.OFPP_FLOOD
            actions=[parser.OFPAActionOutput(out_port)]
            out = parser.OFPPacketOut(datapath = datapath,
                                    buffer_id = msg.buffer_id,
                                    in_port = in_port,
                                    actions = actions,
                                    data = msg.data)

            datapath.send_msg(out)
        return
    elif arp_pkg.opcode == arp.ARP_REPLY:
        if arp_pkg.src_ip not in self.ip_to_mac:
            self.ip_to_mac[arp_pkg.src_ip]=src
            self.mac_to_dpid[src]=(dpid,in_port)
            self.ip_to_port[arp_pkg.src_ip]=(dpid,in_port)
        dst_mac=self.ip_to_mac[arp_pkg.dst_ip]
        dst_dpid,dst_port=self.mac_to_dpid[dst_mac]
        switches = get_switch(self)

        for switch in switches:
            if dst_dpid == switch.dp.id:
                self.arpReply(datapath=switch.dp,port=dst_port,
                    src_mac=src,dst_mac=dst_mac,
                    src_ip=arp_pkg.src_ip,dst_ip=arp_pkg.dst_ip)
        return

```

```

def send_pkt(self, datapath, port, pkt):
    ofp=datapath.ofproto
    parser=datapath.ofproto_parser
    pkt.serialize()
    data=pkt.data
    actions=[parser.OFPACTIONOutput(port=port)]
    out=parser.OFPPacketOut(datapath=datapath,buffer_id=ofp.OFP_NO_BUFFER,
    in_port=ofp.OFPP_CONTROLLER,actions=actions,data=data)
    datapath.send_msg(out)

def arpReply(self, datapath, port, src_mac, dst_mac, src_ip, dst_ip):
    pkt=packet.Packet()
    pkt.add_protocol(ethernet.ethernet(ethertype=0x0806,dst=dst_mac,src=src_mac))
    pkt.add_protocol(arp.arp(opcode=arp.ARP_REPLY,src_mac=src_mac,
    src_ip=src_ip,dst_mac=dst_mac,dst_ip=dst_ip))
    self.send_pkt(datapath,port,pkt)

def handle_ipv4(self, msg, src_ip, dst_ip, pkt_type):
    parser = msg.datapath.ofproto_parser

    dpid_path = self.network_awareness1.shortest_path(src_ip, dst_ip, weight=1)
    if not dpid_path:
        return

    self.path=dpid_path
    # get port path: h1 -> in_port, s1, out_port -> h2
    port_path = []
    for i in range(1, len(dpid_path) - 1):
        in_port = self.network_awareness1.link_info[(dpid_path[i], dpid_path[i+1])]
        out_port = self.network_awareness1.link_info[(dpid_path[i+1], dpid_path[i+2])]
        port_path.append((in_port, dpid_path[i+1], out_port))
    self.show_path(src_ip, dst_ip, port_path)
    # calc path delay

    # send flow mod
    for node in port_path:
        in_port, dpid, out_port = node
        self.send_flow_mod(parser, dpid, pkt_type, src_ip, dst_ip, in_port, out_port)
        self.send_flow_mod(parser, dpid, pkt_type, dst_ip, src_ip, out_port)

    # send packet_out
    _, dpid, out_port = port_path[-1]
    dp = self.network_awareness1.switch_info[dpid]
    actions = [parser.OFPACTIONOutput(out_port)]
    out = parser.OFPPacketOut(datapath=dp, buffer_id=msg.buffer_id, in_port=src_ip,

```



```
dp.send_msg(out)
```

```
def send_flow_mod(self, parser, dpid, pkt_type, src_ip, dst_ip, in_port,
                  dp = self.network_awareness1.switch_info[dpid]
                  match = parser.OFPMatch(
                      in_port=in_port, eth_type=pkt_type, ipv4_src=src_ip, ipv4_dst=dst_ip)
                  actions = [parser.OFPActionOutput(out_port)]
                  self.add_flow(dp, 1, match, actions, 10, 30)

def show_path(self, src, dst, port_path):
    self.logger.info('path: {} -> {}'.format(src, dst))
    path_delay = 0
    path = src + ' -> '
    for i in range(len(port_path)):
        path += '{}:s{}:{}'.format(port_path[i][0], port_path[i][1], port_p

        if i == len(port_path) - 1:
            break
        path_delay += self.network_awareness1.delay[(port_path[i][1], port

    for node in port_path:
        path += '{}:s{}:{}'.format(*node) + ' -> '

    path += dst
    path += " delay=" + '%.1f'%path_delay+ 'ms'
    self.logger.info(path)
```