Ingress firewall implementation FreeRTOS

Politecnico di Torino:
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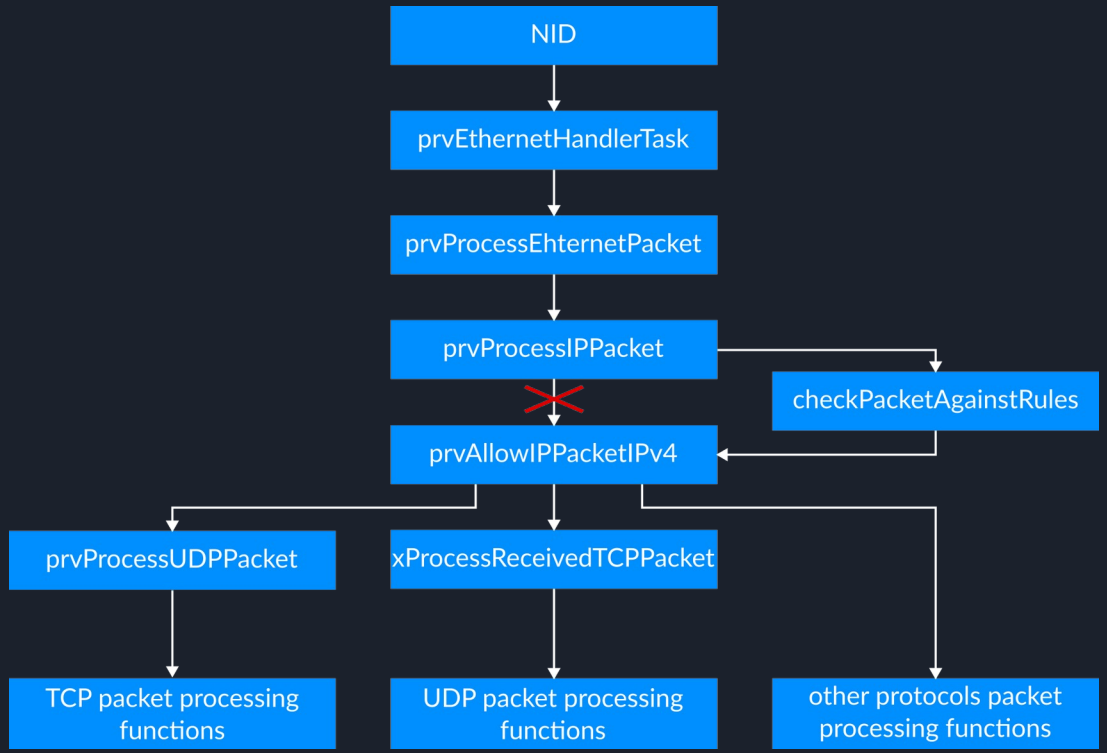
Project intent: create a working firewall for FreeRTOS

- Requirements :
  - Function entry points for filtering packets
  - Handling of rejected packets
    - Print to stderr
  - Rule generation
    - YAML to C struct
  - Rule storage
    - Inline C structs in *rules.h*
  - (WIP) integration with IDS
    - Snort

Understanding FreeRTOS IP stack :
Packet processing pipeline



Functions

```
                    if( ( uxHeaderLength  > ( pxNetworkBuffer ->xDataLength  - ipSIZE_OF_ETH_HEADER  ) ) ||
                        ( uxHeaderLength  < ipSIZE_OF_IPv4_HEADER  )  || checkPacketAgainstRules (ruleset, NOR, pxIPHeader , pxNetworkBuffer ) )
// firewall injection point
                    {
                        eReturn  = eReleaseBuffer ;
                    }
```

FreeRTOS_IP.c:prvProcessIPPacket

packet interception point

```
uint8_t checkPacketAgainstRules (struct rule ruleset[], int num_rules,const IPHeader_t * pxIPHeader , NetworkBufferDescriptor_t  const * pxNetworkBuffer ) {
    //collapse all checks in one function ( fast enough?)
    switch(pxIPHeader ->ucProtocol ){
        case ipPROTOCOL_UDP :{
                const UDPPacket_t  * pxUDPPacket  = ( ( UDPPacket_t  * ) pxNetworkBuffer ->pucEthernetBuffer  );
                const UDPHeader_t  * pxUDPHeader  =  &( pxUDPPacket ->xUDPHeader );
 //Get the header of the UDP packet from the pxNetworkBuffer to extract the ports
                if (checkPacketsWithPorts (ruleset, num_rules, pxIPHeader , pxUDPHeader ->usSourcePort , pxUDPHeader ->usDestinationPort ) == 1){
                    writeToPcap (pxIPHeader , pxUDPHeader ->usSourcePort , pxUDPHeader ->usDestinationPort );
 //If the packet is rejected by the rules pass to loggin function
                    return 1;
                }
                return 0;
        }
            break;
        case ipPROTOCOL_TCP :{
                const ProtocolHeaders_t  *pxProtocolHeaders  = ( ( ProtocolHeaders_t  * ) &( pxNetworkBuffer ->pucEthernetBuffer [ ipSIZE_OF_ETH_HEADER  +
uxIPHeaderSizePacket ( pxNetworkBuffer  ) ] ) );
                //construct to get to the TCP header fields
                if (checkPacketsWithPorts (ruleset, num_rules, pxIPHeader , pxProtocolHeaders ->xTCPHeader .usSourcePort , pxProtocolHeaders ->xTCPHeader .
usDestinationPort )==1){
                    writeToPcap (pxIPHeader , pxProtocolHeaders ->xTCPHeader .usSourcePort , pxProtocolHeaders ->xTCPHeader .usDestinationPort );
                    return 1; //return 1 discards the packet
                }
                return 0;
            break;
        }
        case ipPROTOCOL_ICMP :{
            ICMPPacket_t  * pxICMPPacket  = ( ( ICMPPacket_t  * ) pxNetworkBuffer ->pucEthernetBuffer  ); //ICMP doesn't need ports
            if (checkIPs (ruleset, num_rules , (IPHeader_t *)& (pxICMPPacket ->xIPHeader )) == 1){
                writeToPcap (pxIPHeader , 0, 0);
                return 1;
            }
                return 0;
        }
        default :{
            if (checkIPs (ruleset, num_rules , pxIPHeader ) == 1){ //other protocols like ARP
                writeToPcap (pxIPHeader , 0, 0);
                return 1;
            }
                return 0;
        }

    }
}
```

FreeRTOS_IP.c:checkPacketAgainstRules

```
uint8_t checkIPs (struct rule ruleset[], int num_rules , const IPHeader_t * pxIPHeader ){
    int i;
    for (i = 0; i < num_rules ; i++) {
        if (pxIPHeader ->ulSourceIPAddress  == ruleset [i].src &&
            pxIPHeader ->ulDestinationIPAddress  == ruleset [i].dst &&
            pxIPHeader ->ucProtocol  == ruleset [i].proto ) {
            return ruleset [i].action; // match found execute corresponding action on the packet
        }
    }
    return 1; // no match found being this a block list we just let the packet trough
};

uint8_t checkPacketsWithPorts (struct rule ruleset[], int num_rules , const IPHeader_t * pxIPHeader , uint16_t usSourcePort , uint16_t
usDestinationPort ) { //collapse all checks in one function ( fast enough?)
    int i;
    for (i = 0; i < num_rules ; i++) {
        if(pxIPHeader ->ucProtocol ==6){
        if (pxIPHeader ->ulSourceIPAddress  == ruleset [i].src &&
            pxIPHeader ->ulDestinationIPAddress  == ruleset [i].dst &&
            usSourcePort  == ruleset [i].port_src && // convert port to network byte order
            usDestinationPort  == ruleset [i].port_dst && // convert port to network byte order
            pxIPHeader ->ucProtocol == ruleset [i].proto) {
            return ruleset [i].action;
 // match found execute corresponding action on the packet this can be used both as blakclist and whitelist.
        }
        }
        else if (pxIPHeader ->ucProtocol ==17){
            printf("%d ", usSourcePort );
            printf("%d ", usDestinationPort );
            if (pxIPHeader ->ulSourceIPAddress  == ruleset [i].src &&
            pxIPHeader ->ulDestinationIPAddress  == ruleset [i].dst &&
            usSourcePort  == ruleset [i].port_src && // convert port to network byte order -> done in the preprocessor for the rules
            usDestinationPort  == ruleset [i].port_dst && // convert port to network byte order -> done in the preprocessor for the rules
            pxIPHeader ->ucProtocol  == ruleset [i].proto ) {
            return ruleset [i].action;
 // match found execute corresponding action on the packet this can be used both as blakclist and/or whitelist.
        }
        }
    }

    return 1; // no match found being this a allow list we just let the packet trough
};
```

FreeRTOS_IP.c:checkIPs & checkPacketsWithPort

Handling of rejected packets

```
void writeToPcap(const IPHeader_t * pxIPHeader, uint16_t usSourcePort, uint16_t usDestinationPort ){
        //Print to serial console with identifier : clamp fields : and output

//Write the discarded packets data to stderr -> quemu write output to file -> process in PCAP only the lines with  #PCAP -> export in Wireshark
        fprintf(stderr,"#PCAP %d %d %d %d %d  \n", pxIPHeader->ulSourceIPAddress, pxIPHeader->ulDestinationIPAddress , pxIPHeader->ucProtocol,
usSourcePort, usDestinationPort );
}
```

FreeRTOS_IP.c:writeToPcap

- write the data of the rejected packets in *stderr*
  - marking every rejected packet with *#PCAP*
- pipe the *qemu-system-arm* output, that is all directed to *stderr*, to a file out.log
- process the file to compile a *pcap*

```
import socket
import struct
import dpkt
import re

def get_initial_ip(ip_int):
    oct_arr = [(ip_int >> 24) & 255, (ip_int >> 16) & 255, (ip_int >> 8) & 255, ip_int & 255]
    oct_arr.reverse()
    ip_str = ".".join(map(str, oct_arr))
    return ip_str

def get_initial_port(port_int):
    port_int = int(port_int)
    port_int = ((port_int & 0xFF) << 8) | ((port_int >> 8) & 0xFF)
    return port_int

with open('../PART_3/out.log', 'r') as file:
    with open('./output.pcap', 'wb') as pcap_file:

        pcap_writer = dpkt.pcap.Writer(pcap_file)
        for line in file:

            if line.startswith('#PCAP'):
                # Extract the relevant information using regular expressions
                match = re.match(r'#PCAP (\d+) (\d+) (\d+) (\d+) (\d+)', line)
                if match:
                    source_ip = get_initial_ip(int(match.group(1)))
                    destination_ip = get_initial_ip(int(match.group(2)))
                    source_port = get_initial_port(int(match.group(4)))
                    destination_port = get_initial_port(int(match.group(5)))
                    protocol = int(match.group(3))

                    eth = dpkt.ethernet.Ethernet()

                    if protocol == 6:
                        tcp = dpkt.tcp.TCP()
                        tcp.sport = source_port
                        tcp.dport = destination_port
                        tcp.data = b'TCP packet'
                        ip = dpkt.ip.IP(src=socket.inet_aton(source_ip), dst=socket.inet_aton(
destination_ip), p=dpkt.ip.IP_PROTO_TCP)
                        ip.data = tcp
                        eth.data = ip
                    elif protocol == 17:
                        udp = dpkt.udp.UDP()
                        udp.sport = source_port
                        udp.dport = destination_port
                        udp.data = b'UDP packet'
                        ip = dpkt.ip.IP(src=socket.inet_aton(source_ip), dst=socket.inet_aton(
destination_ip), p=dpkt.ip.IP_PROTO_UDP)
                        ip.data = udp
                        eth.data = ip
                    elif protocol == 1:
                        # Create an ICMP packet
                        icmp = dpkt.icmp.ICMP()
                        icmp.type = dpkt.icmp.ICMP_ECHO
                        icmp.data = b'ICMP packet'
                        ip = dpkt.ip.IP(src=socket.inet_aton(source_ip), dst=socket.inet_aton(
destination_ip), p=dpkt.ip.IP_PROTO_ICMP)
                        ip.data = icmp
                        eth.data = ip
                    else:
                        ip = dpkt.ip.IP(src=socket.inet_aton(source_ip), dst=socket.inet_aton(
destination_ip))
                        eth.data = ip

                    pcap_writer.writepkt(eth)

# Print a message to indicate the completion of the task
print('Packets written to output.pcap file.')
```

Python .log to PCAP conversion function

Rules generation

```yaml
ruleset:
  - source: 192.168.122.50
    destination: 192.168.122.10
    port_source: 200
    port_destination: 4050
    protocol: 17
    action: 0
  - source: 192.168.122.1
    destination: 192.168.122.10
    port_source: 200
    port_destination: 33
    protocol: 6
    action: 0
  - source: 192.168.122.1
    destination: 192.168.122.10
    port_source: ANY
    port_destination: ANY
    protocol: 1
    action: 0
```

rules.yaml

Rules storage

```c
#ifndef __RULE_SET_FIREWALL_
#define __RULE_SET_FIREWALL_  1

  #include <stdlib.h>

  #define NOR 3

  //A Firewall rule structure
  typedef struct rule {
      uint32_t src;  // Source IP address in network byte order
      uint32_t dst;  // Destination IP address in network byte order
      uint16_t port_src; // Source port number in network byte order
      uint16_t port_dst; // Destination port number in network byte order
      uint8_t proto; // 2-bit mask representing protocol type
      uint8_t action;
 //action to do with packets from the source ip 0 >> accept packets 1 >> reject packets
  }Rule;

  //Current ruleset loaded in the firewall
  Rule ruleset[NOR] = {
      {846899392, 175810752, 51200, 53775, 17, 0 },
      {24815808, 175810752, 51200, 8448, 6, 0 },
      {24815808, 175810752, 0, 0, 1, 0 },
  };

#endif
```

FreeRTOS-Plus-TCP/rules.h:

Tests for rules and output PCAP

```
send(IP(dst="192.168.122.10",src="192.168.122.50")/UDP(dport=4050,sport=200)/Raw(load="abc"),
iface="virbr0")
send(IP(dst="192.168.122.10",src="192.168.122.1")/TCP(dport=33,sport=200), iface="virbr0")
send(IP(dst="192.168.122.10",src="192.168.122.1")/ICMP(), iface="virbr0")
send(IP(dst="192.168.122.10",src="192.168.122.50")/UDP(dport=3050,sport=200)/Raw(load="def"),
iface="virbr0")
send(IP(dst="192.168.122.10",src="192.168.122.1")/TCP(dport=6968,sport=200), iface="virbr0")
send(IP(dst="192.168.122.10",src="192.168.122.50")/ICMP(), iface="virbr0")
```

Packet generation calls that are fed to **scapy :** 6 packets 3 of which are expected to be rejected by the rules defined earlier

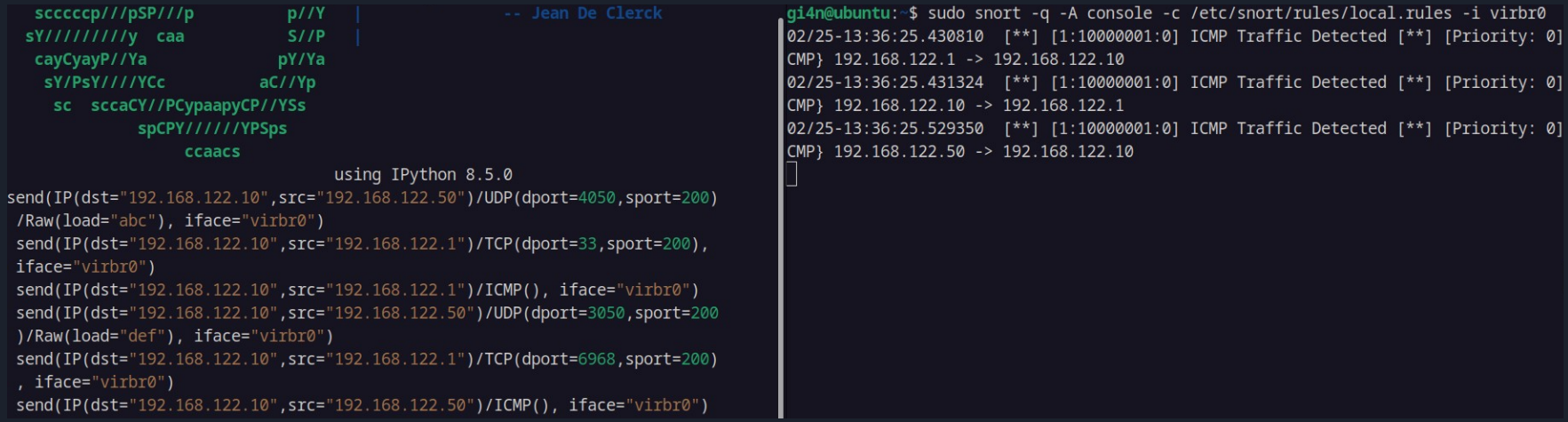
Apply a display filter ... <Ctrl-/>

No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	192.168.122.50	192.168.122.10	UDP	52	200 → 3050 Len=0
2	0.000055	192.168.122.1	192.168.122.10	TCP	64	200 → 6968 [SYN] Seq=0 Win=65535 Len=10
3	0.000140	192.168.122.50	192.168.122.10	ICMP	49	Echo (ping) request id=0x4943, seq=19792/20557, ttl=64 (no response found!)

The 3 rejected packets as expected

Integration of IDS

- preliminary work for POC using SNORT to process rejected packets by the firewall
- needs second NIC or SNORT endpoint with TCP retransmission mechanism



Rules defined to monitoring only the ICMP packets through SNORT, only proof of concept needs more work

Thanks !

And now time for the live demo 🤷