Exploiting Sequence Number Leakage: TCP Hijacking in NAT-Enabled Wi-Fi Networks

Yuxiang Yang, Xuewei Feng, Qi Li, Kun Sun, Ziqiang Wang, Ke Xu

Overview

- Threat Model
- Background
- Attack Procedure
- Empirical Study
- Disclosure and Mitigation
- Conclusion

Threat Model

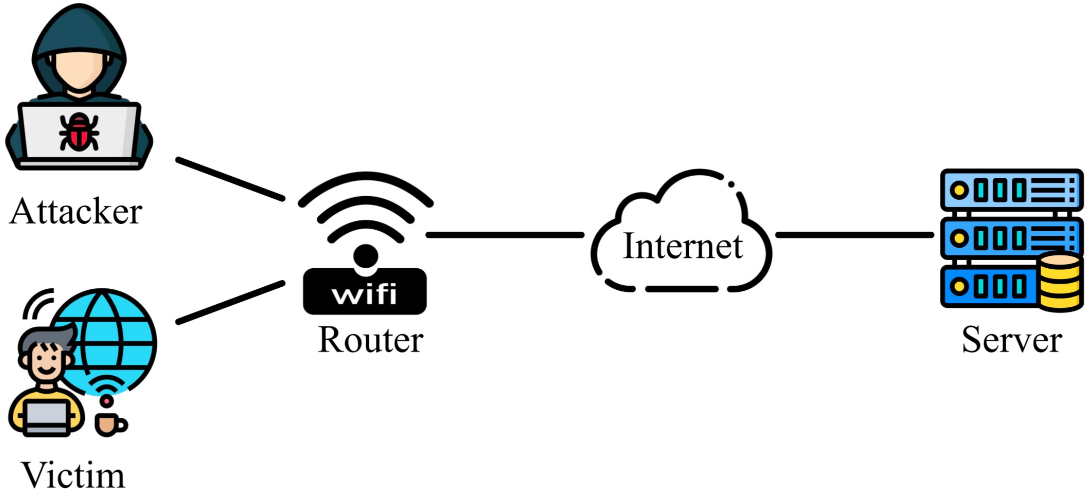
Threat Model

✎Consists of:

- An arbitrary remote **server**
- A **router**, providing Wi-Fi
- A victim **client** who connected to Wi-Fi
- An off-path **attacker** who can access the same Wi-Fi

✎The attack can be used towards:

- TCP **connection termination** attack
- TCP **packets hijacking** attack
- Malicious **data injection** attack



Background

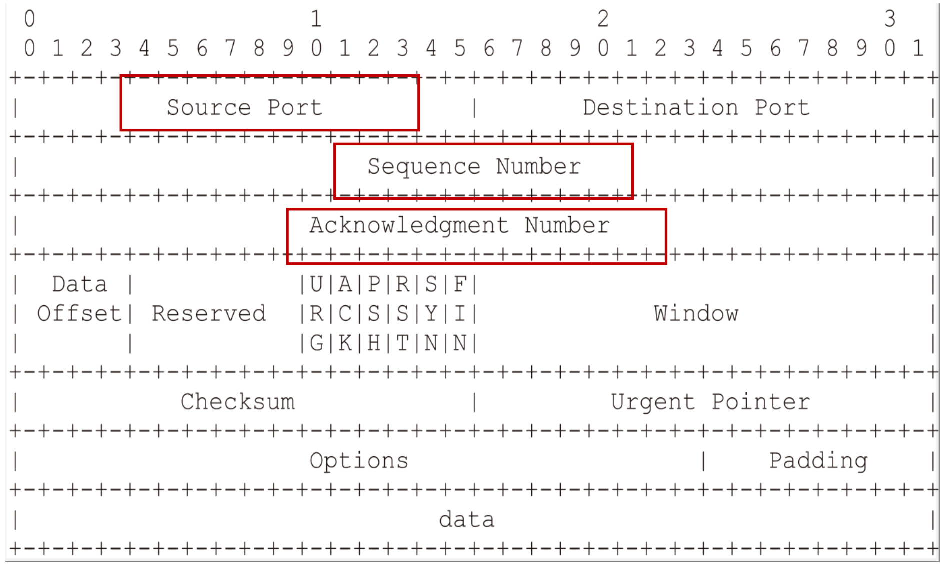
History of TCP Hijacking Attacks

✎ **Given a target server, we already know:**

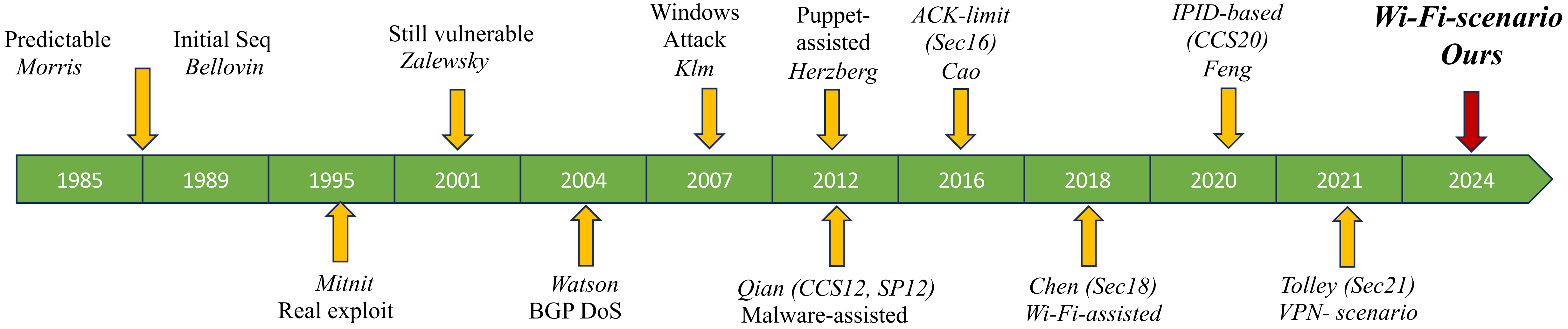
- Src IP address: client's public IP (the same as the attacker)
- Dst IP address: server IP
- Dst Port number: service at server (e.g. 80)

✎ **We want to know:**

- **Src Port number** • **SEQ number** • **ACK number**



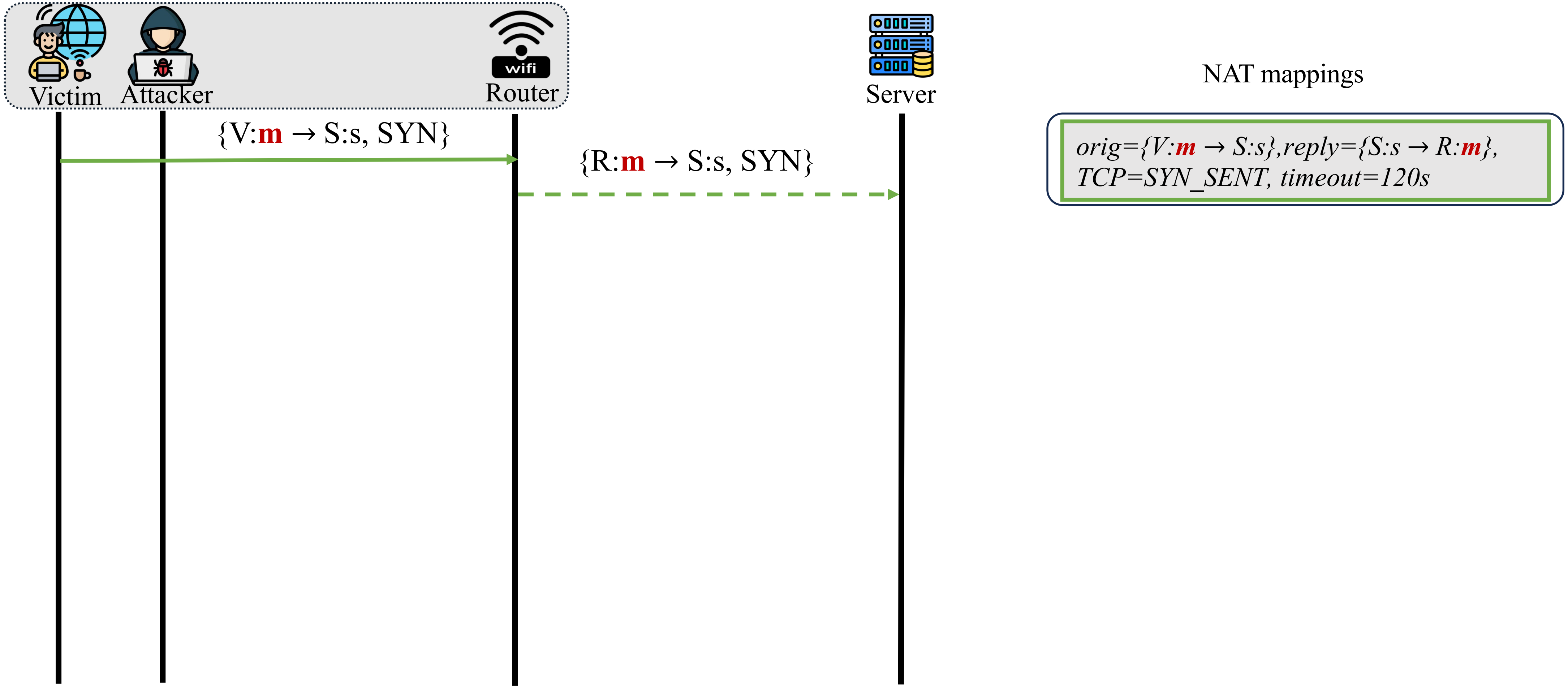
```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|          Source Port          |       Destination Port        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Sequence Number                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Acknowledgment Number                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Data |           |U|A|P|R|S|F|                               |
| Offset| Reserved  |R|C|S|S|Y|I|            Window             |
|       |           |G|K|H|T|N|N|                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|           Checksum            |         Urgent Pointer        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Options                    |    Padding    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                             data                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```



NAT and Port Allocation Strategies

✏**NAT Port Allocation Method:**

(1) random allocation; (2) per-destination sequential; (3) **port preserving allocation**



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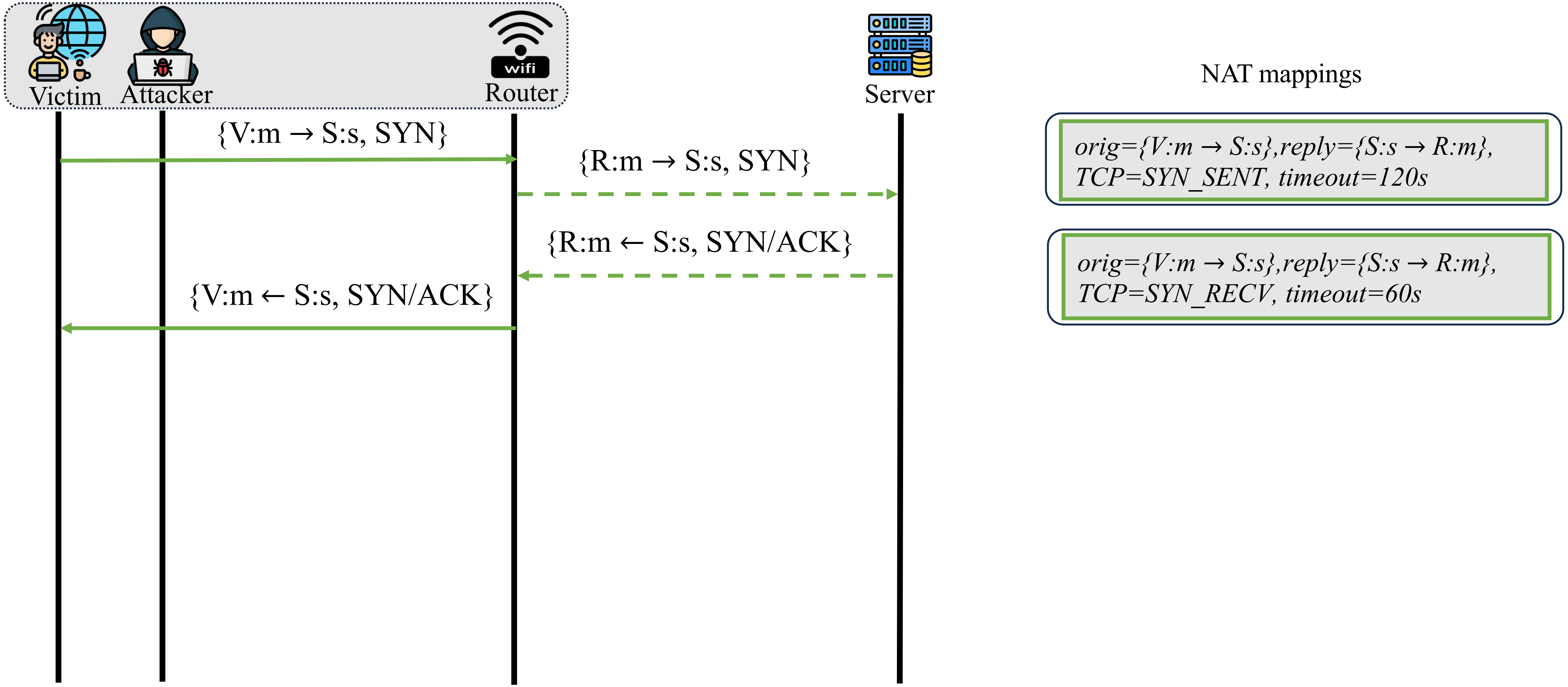

orig={V:m → S:s},reply={S:s → R:m}, TCP=SYN_SENT, timeout=120s

orig={V:m → S:s},reply={S:s → R:m}, TCP=SYN_RECV, timeout=60s

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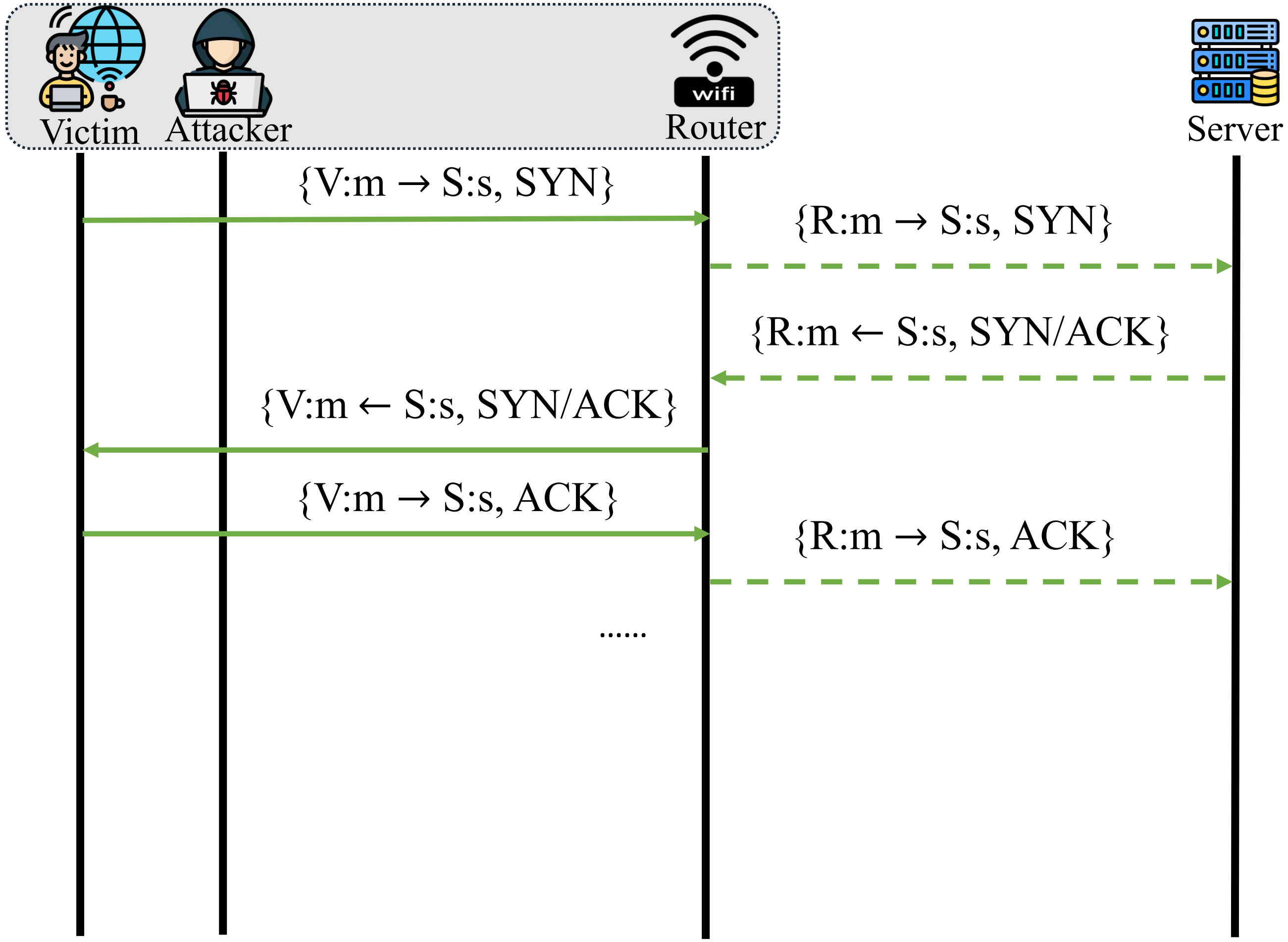

NAT mappings

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orig={V:m → S:s},reply={S:s → R:m}, TCP=ESTABLISHED, timeout=432000s

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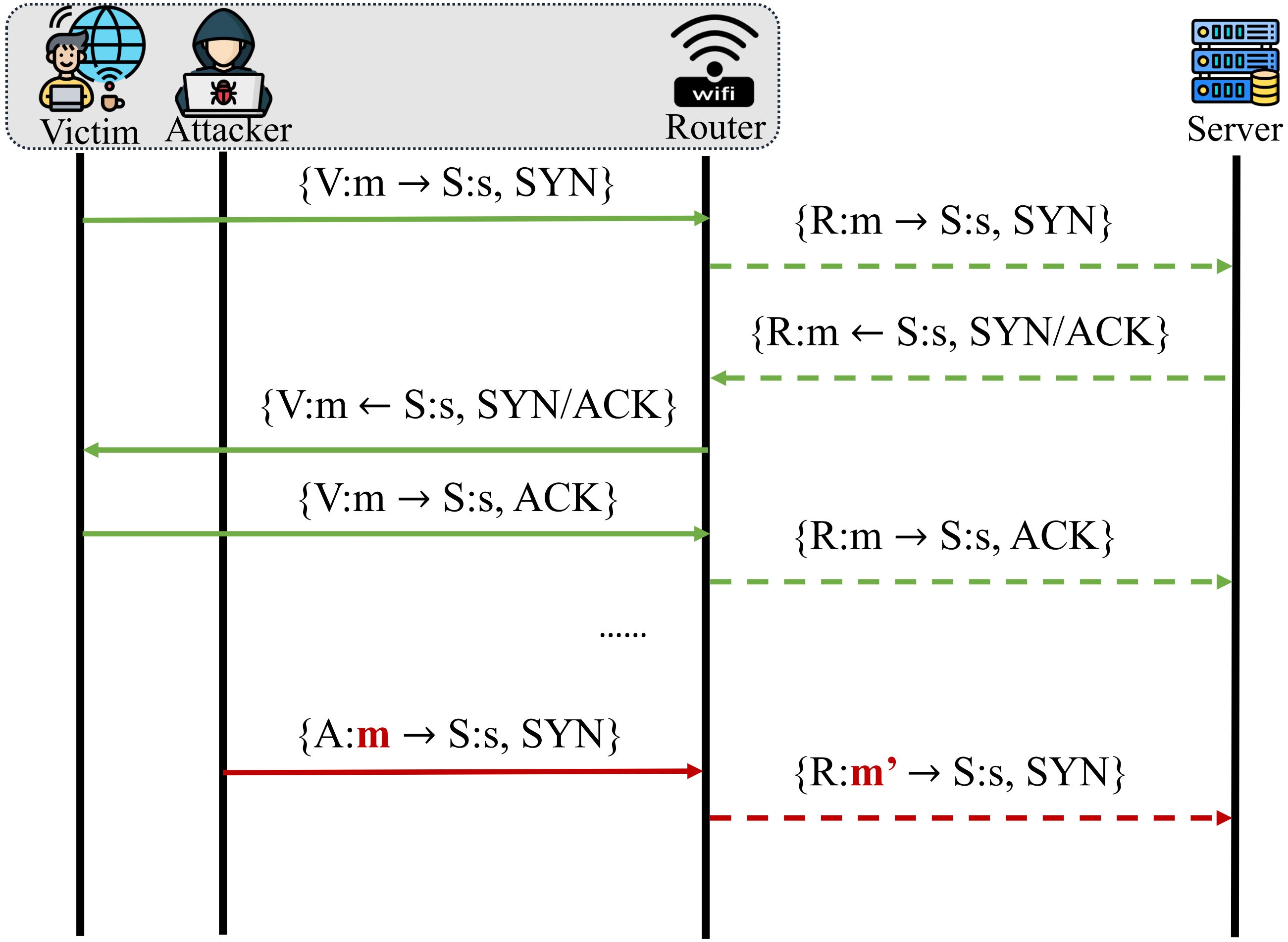

{V:m → S:s, SYN}

{R:m → S:s, SYN}

{R:m ← S:s, SYN/ACK}

{V:m ← S:s, SYN/ACK}

{V:m → S:s, ACK}

{R:m → S:s, ACK}

......

{A:**m** → S:s, SYN}

{R:**m’** → S:s, SYN}

NAT mappings

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TCP=SYN_SENT, timeout=120s

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orig={V:m → S:s},reply={S:s → R:m},
TCP=ESTABLISHED, timeout=432000s

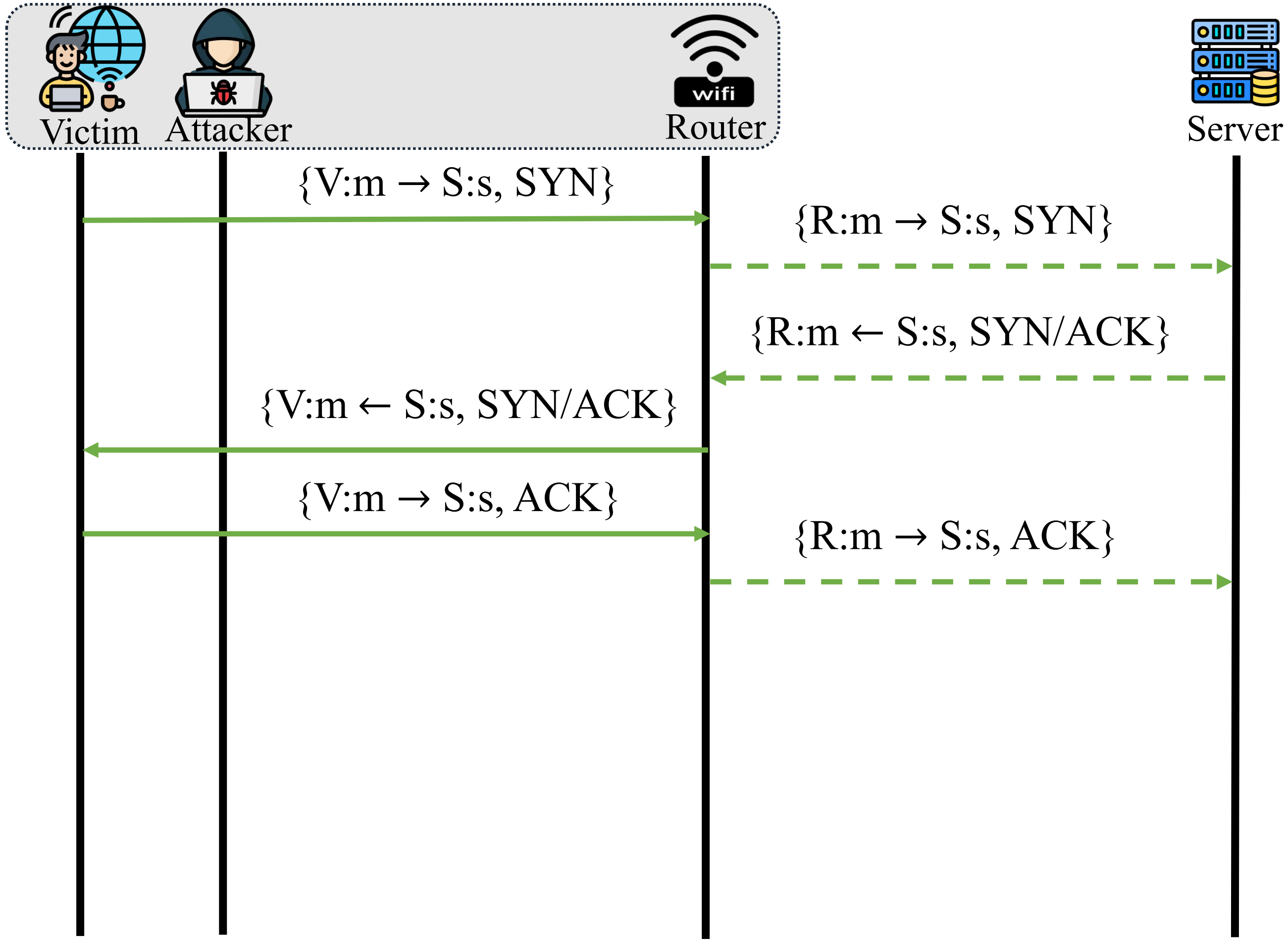
......

orig={V:m → S:s},reply={S:s → R:m},
TCP=ESTABLISHED, timeout=430999s

*orig={A:**m** → S:s},reply={S:s → R:**m’**},*
TCP= SYN_SENT, timeout=120s

TCP Window Tracking in Routers

Due to many reasons, router will not track the TCP window of the connection, and thus it **will not check the sequence** and acknowledgment **numbers** of TCP packets strictly.



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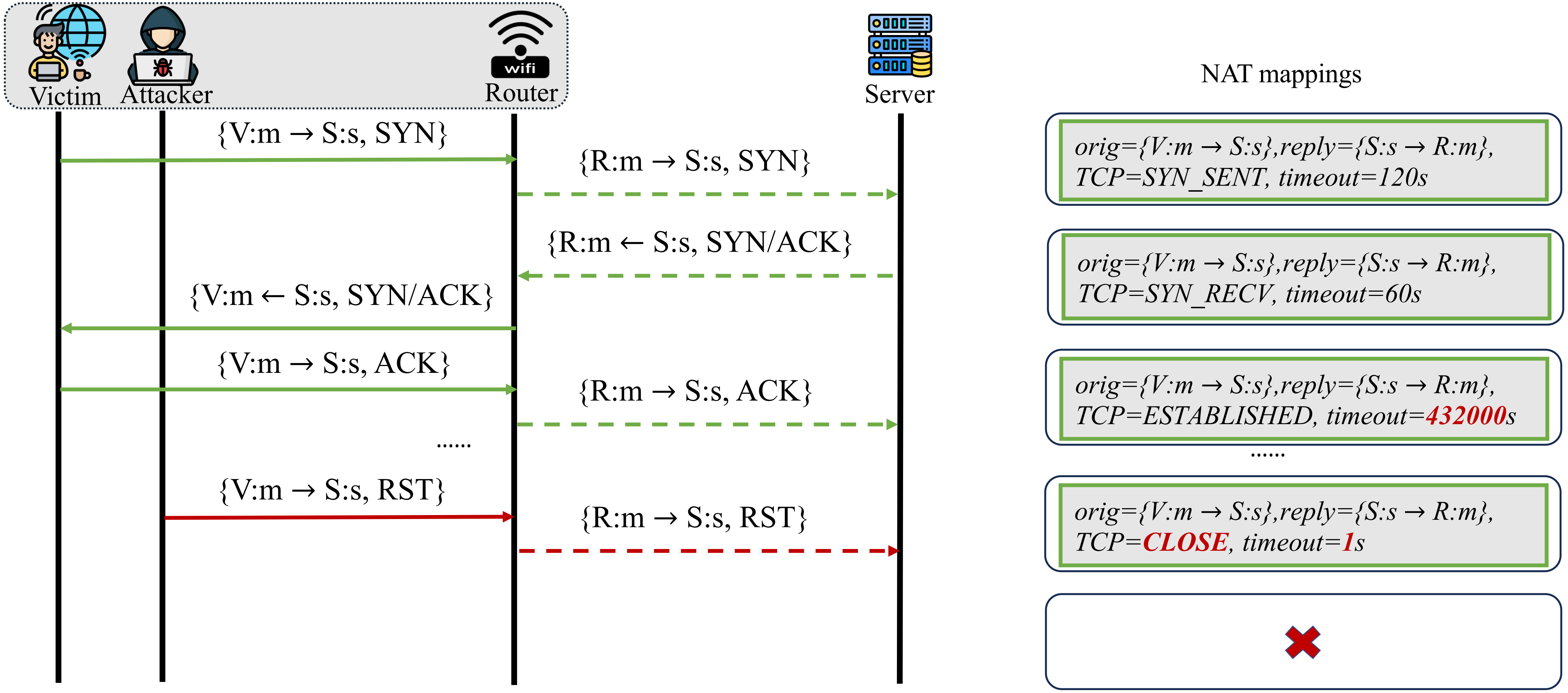

Victim

Attacker

Router

Server

NAT mappings

{V:m → S:s, SYN}

{R:m → S:s, SYN}

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{R:m ← S:s, SYN/ACK}

{V:m ← S:s, SYN/ACK}

orig={V:m → S:s},reply={S:s → R:m},
TCP=SYN_RECV, timeout=60s

{V:m → S:s, ACK}

{R:m → S:s, ACK}

orig={V:m → S:s},reply={S:s → R:m},
*TCP=ESTABLISHED, timeout=**432000**s*

......

......

{V:m → S:s, RST}

{R:m → S:s, RST}

orig={V:m → S:s},reply={S:s → R:m},
*TCP=**CLOSE**, timeout=**1**s*

✗

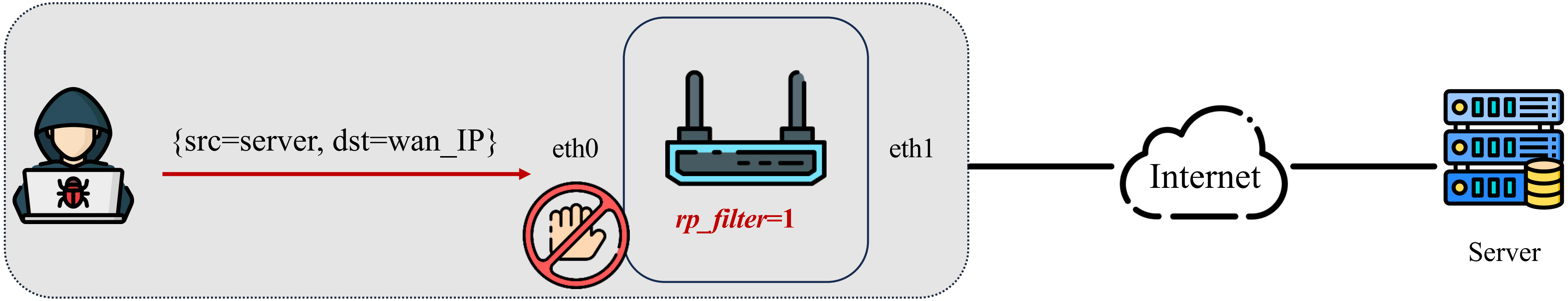
Reverse Path Validation

✎ **Proposed by RFC 3704, to prevent IP spoofing attacks**

- verifies inbound traffic by checking whether **the source IP address** can **be routed back via the interface** on which packets are received against the routing table.

✎ **Controlled by the *rp_filter* kernel variable.**

- 0: disabled;
- 1: Strict Mode;
- 2: Loose Mode



Reverse Path Validation

- **Proposed by RFC 3704, to prevent IP spoofing attacks**
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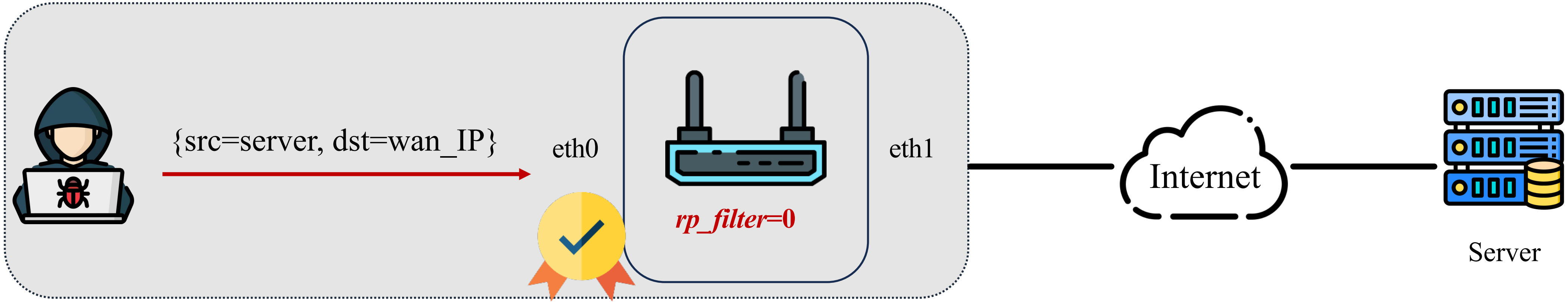
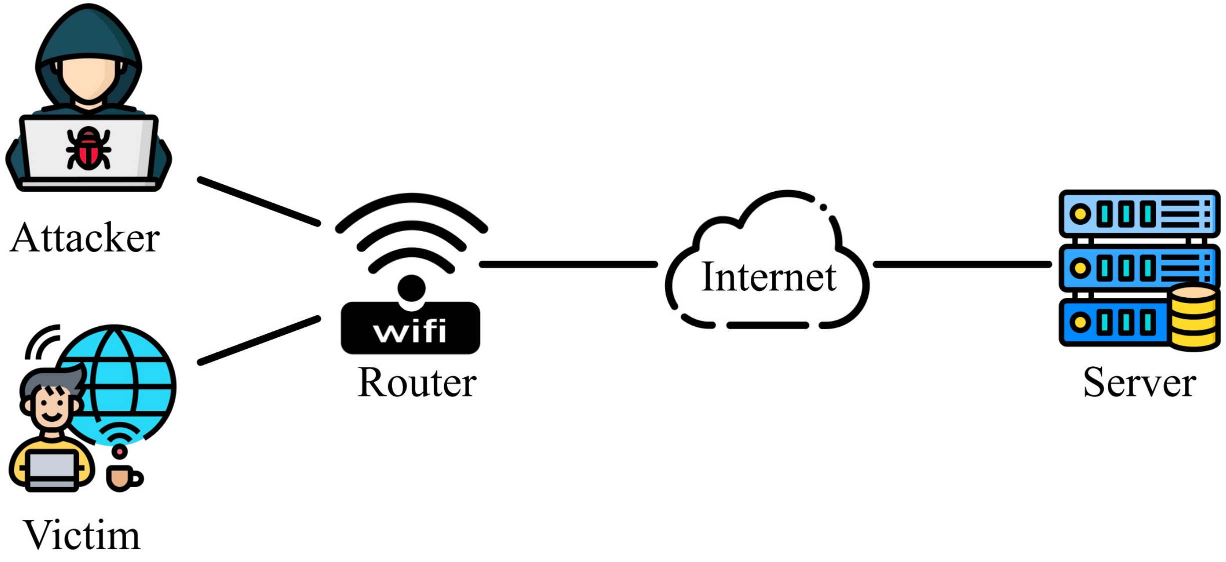


ATTACK PROCEDURE

Attack Overview

✎ **Attack Steps:**

- Step 1: Probing the Wi-Fi Network (to get the **router's external IP** address)
- Step 2: Making Inferences about Active Connections (to infer the **source port** number)
- Step 3: Hijacking Active Connections (to get the **SEQ and ACK** numbers)



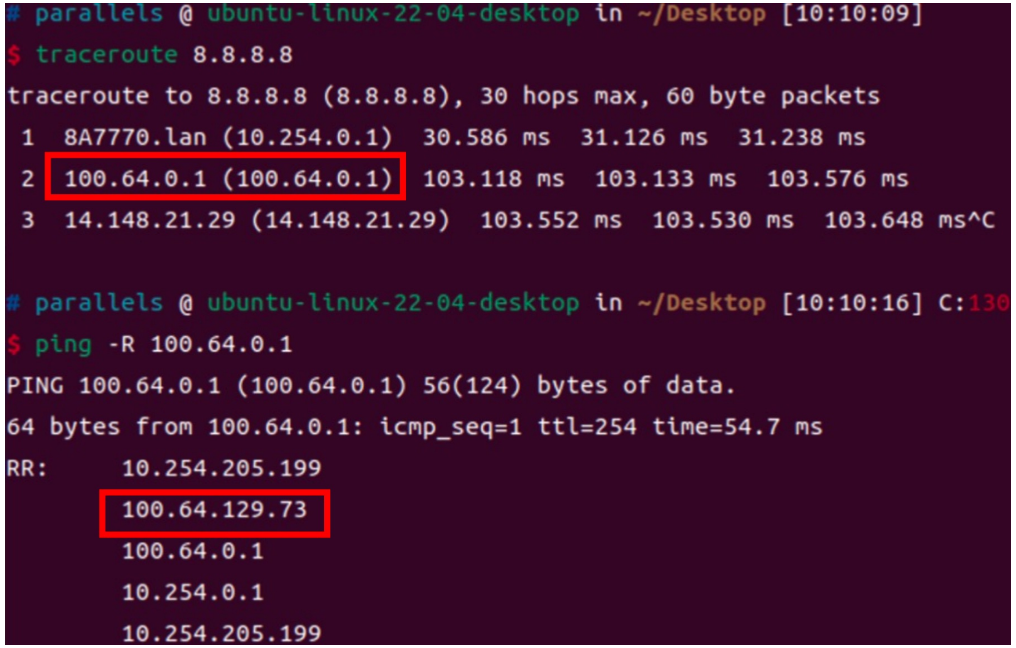
Probing the Network

✎ Identifying the status of AP isolation in the network

- Nmap, MacStealer

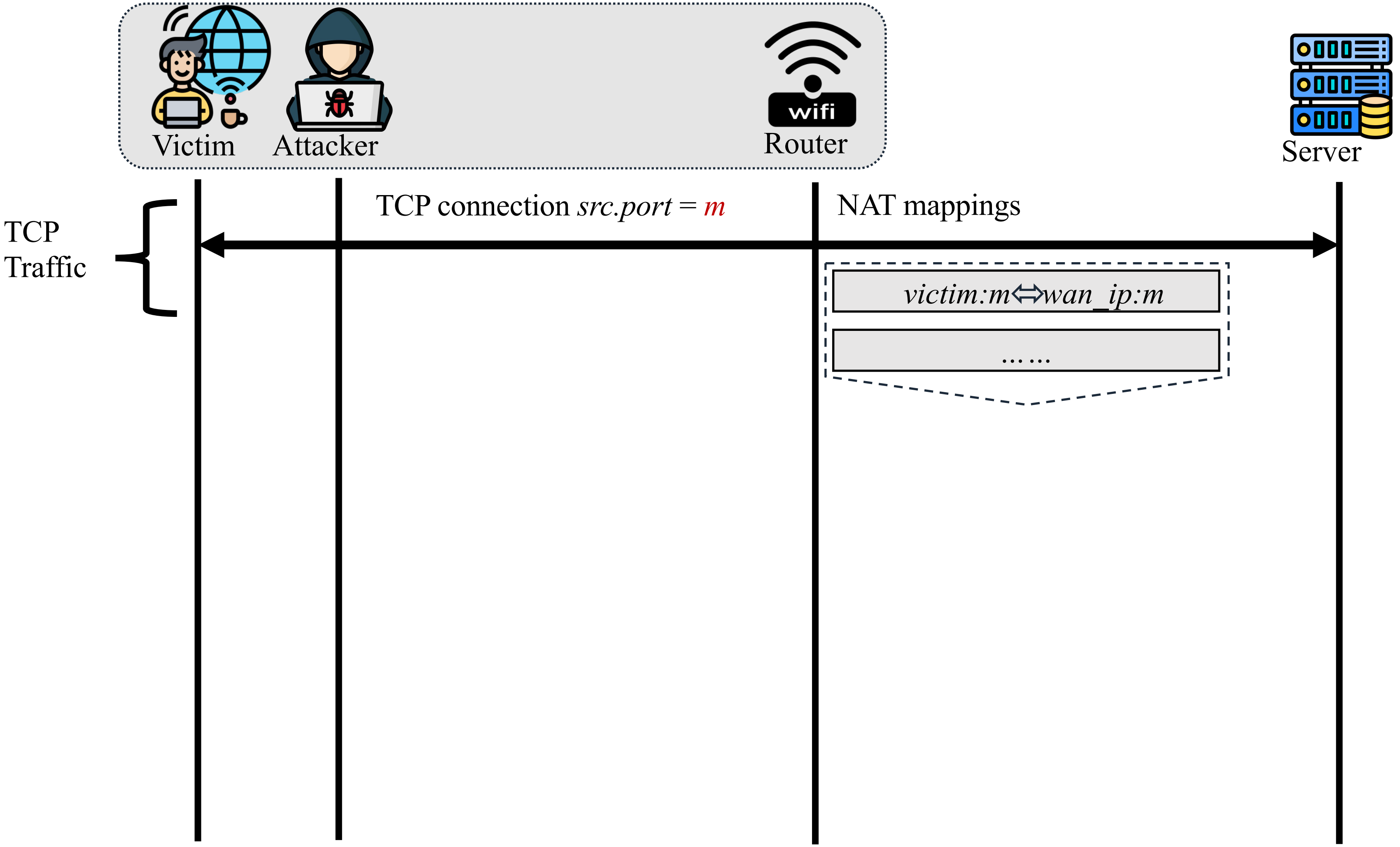
✎ Probing the external IP address of the router

- TraceRoute and Ping with RECORD_ROUTE Option.
- Scan and access IPs via web browsers.



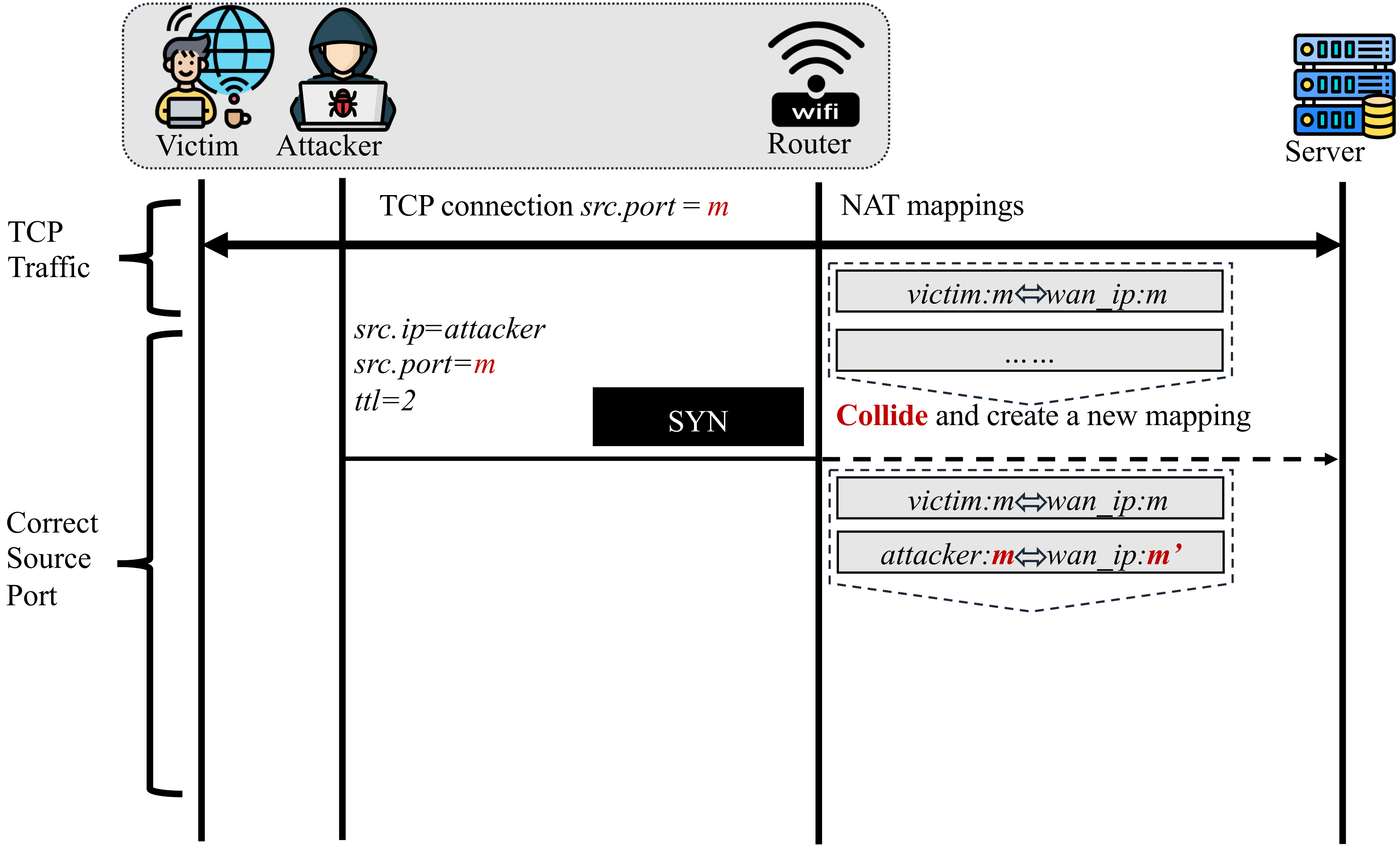
```
# parallels @ ubuntu-linux-22-04-desktop in ~/Desktop [10:10:09]
$ traceroute 8.8.8.8
traceroute to 8.8.8.8 (8.8.8.8), 30 hops max, 60 byte packets
 1  8A7770.lan (10.254.0.1)  30.586 ms  31.126 ms  31.238 ms
 2  100.64.0.1 (100.64.0.1)  103.118 ms  103.133 ms  103.576 ms
 3  14.148.21.29 (14.148.21.29)  103.552 ms  103.530 ms  103.648 ms^C

# parallels @ ubuntu-linux-22-04-desktop in ~/Desktop [10:10:16] C:130
$ ping -R 100.64.0.1
PING 100.64.0.1 (100.64.0.1) 56(124) bytes of data.
64 bytes from 100.64.0.1: icmp_seq=1 ttl=254 time=54.7 ms
RR:     10.254.205.199
        100.64.129.73
        100.64.0.1
        10.254.0.1
        10.254.205.199
```

Making Inferences about Active Connections



Guess when the source port **has been used** by the victim.

Making Inferences about Active Connections



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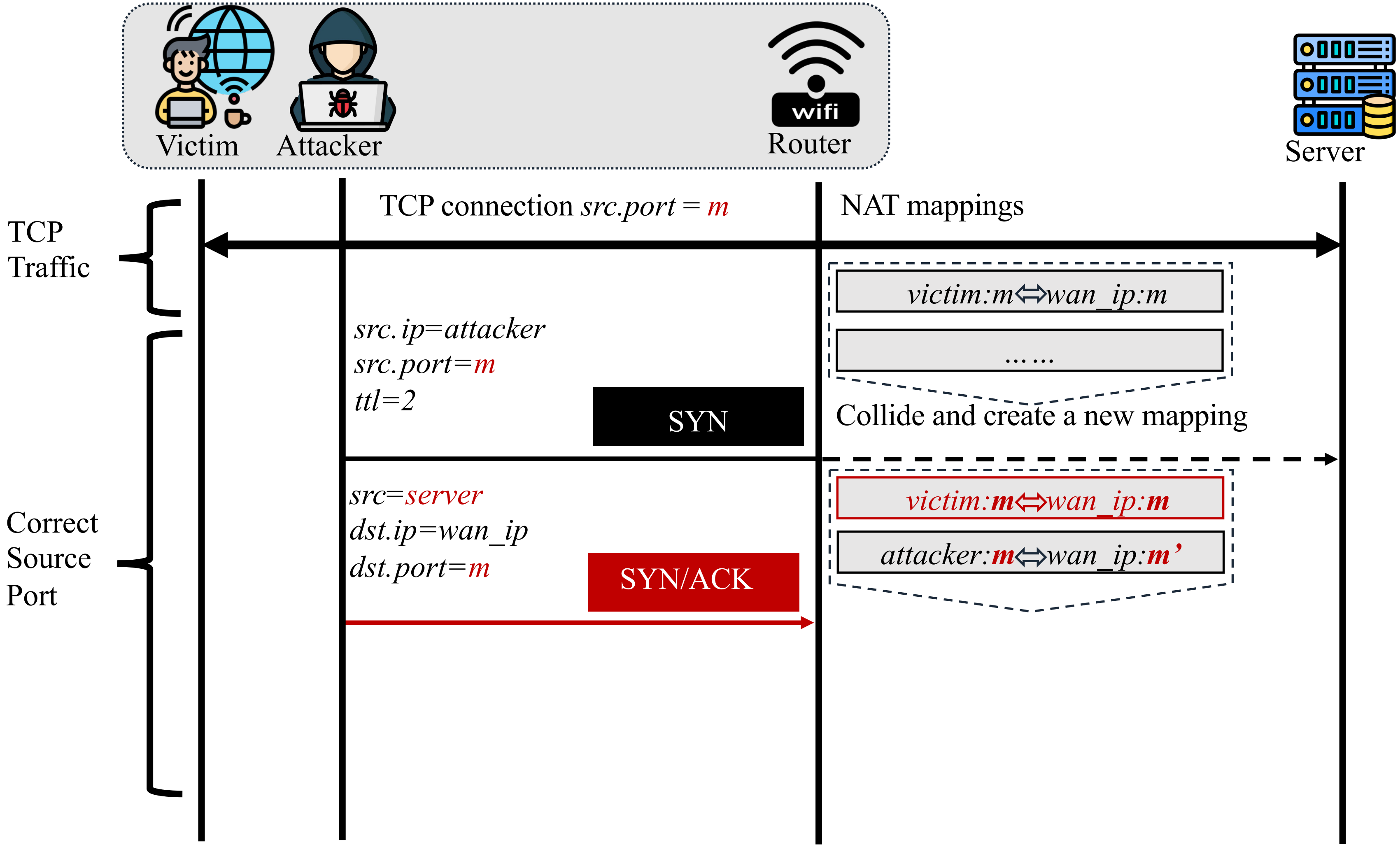

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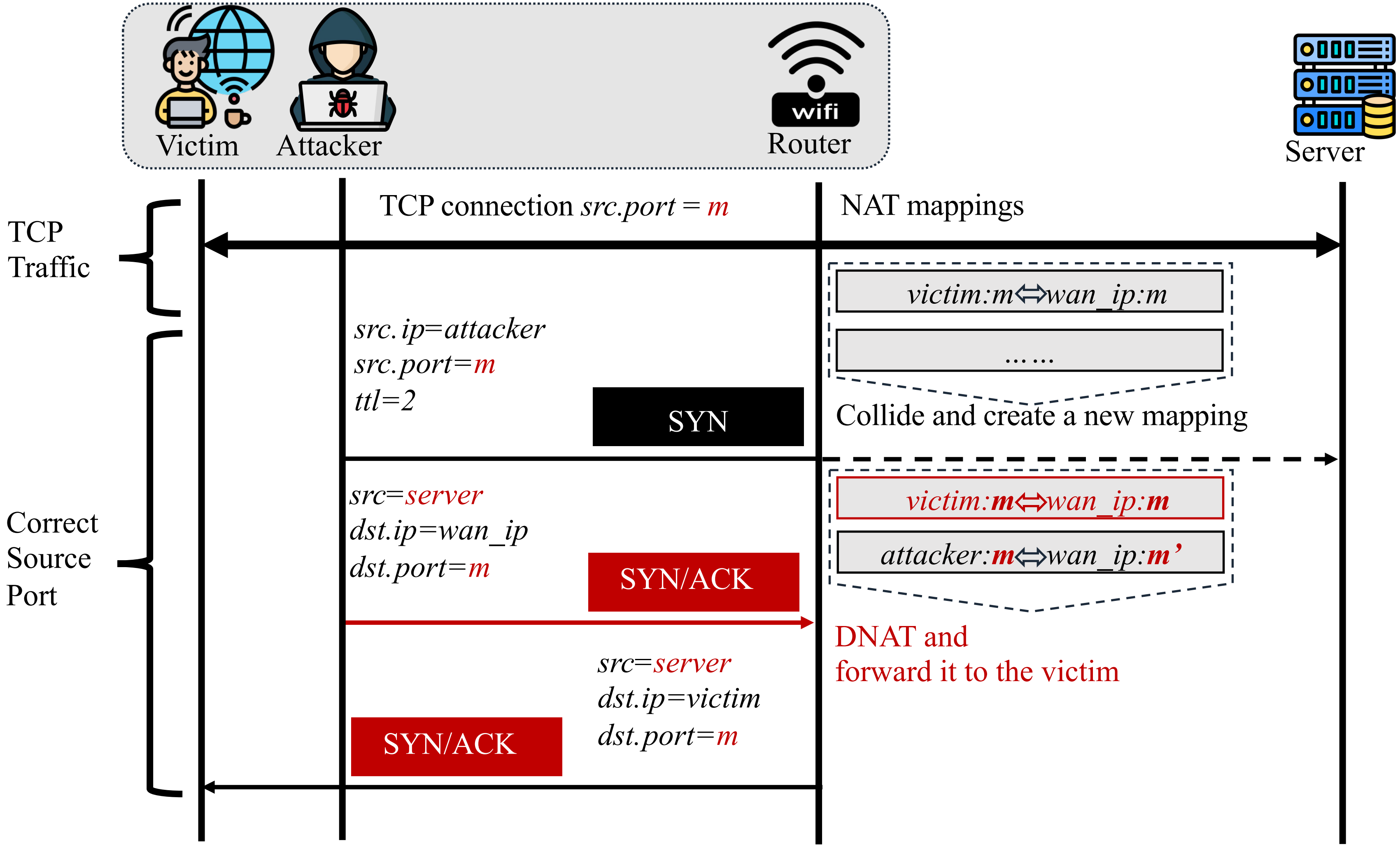

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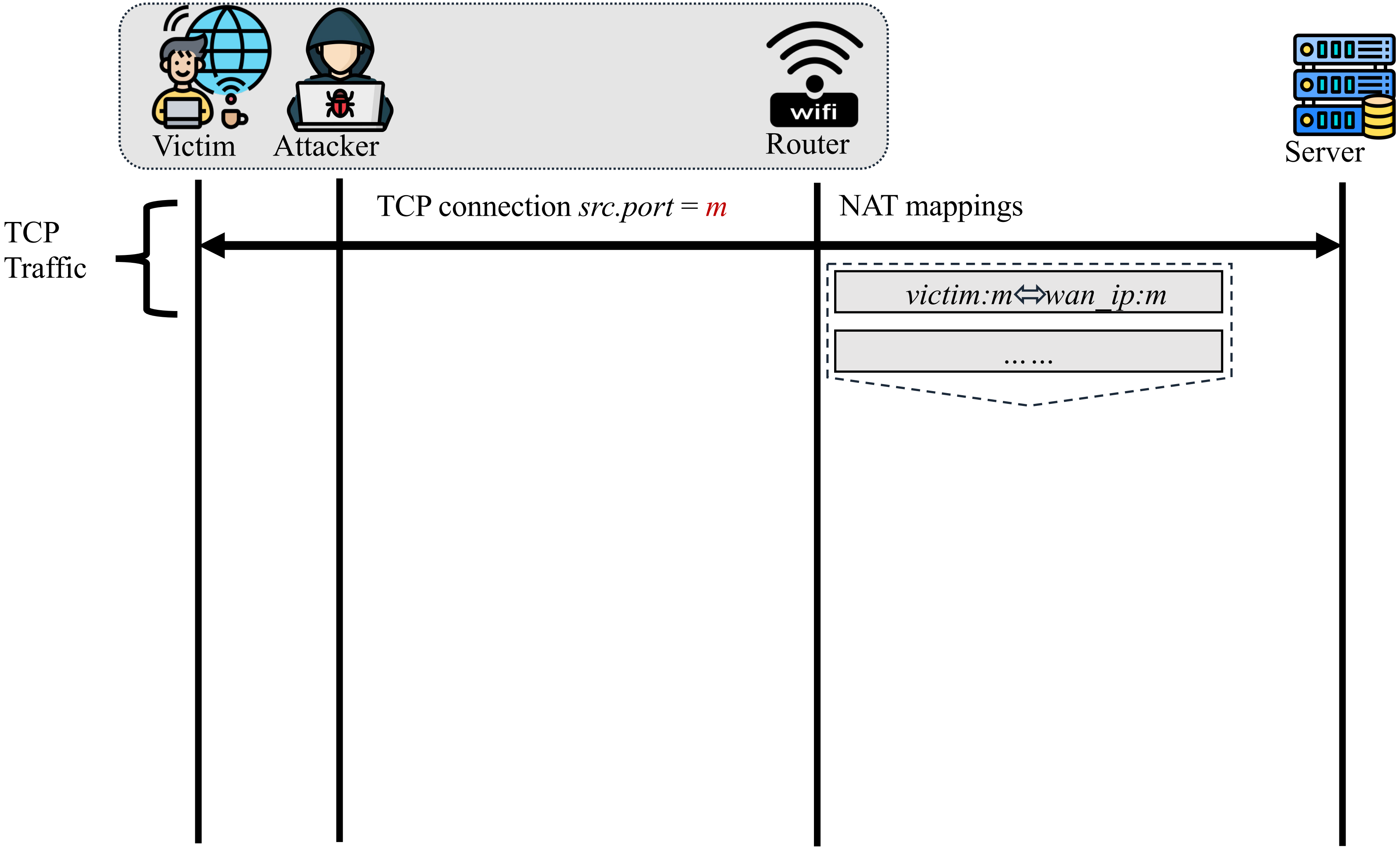
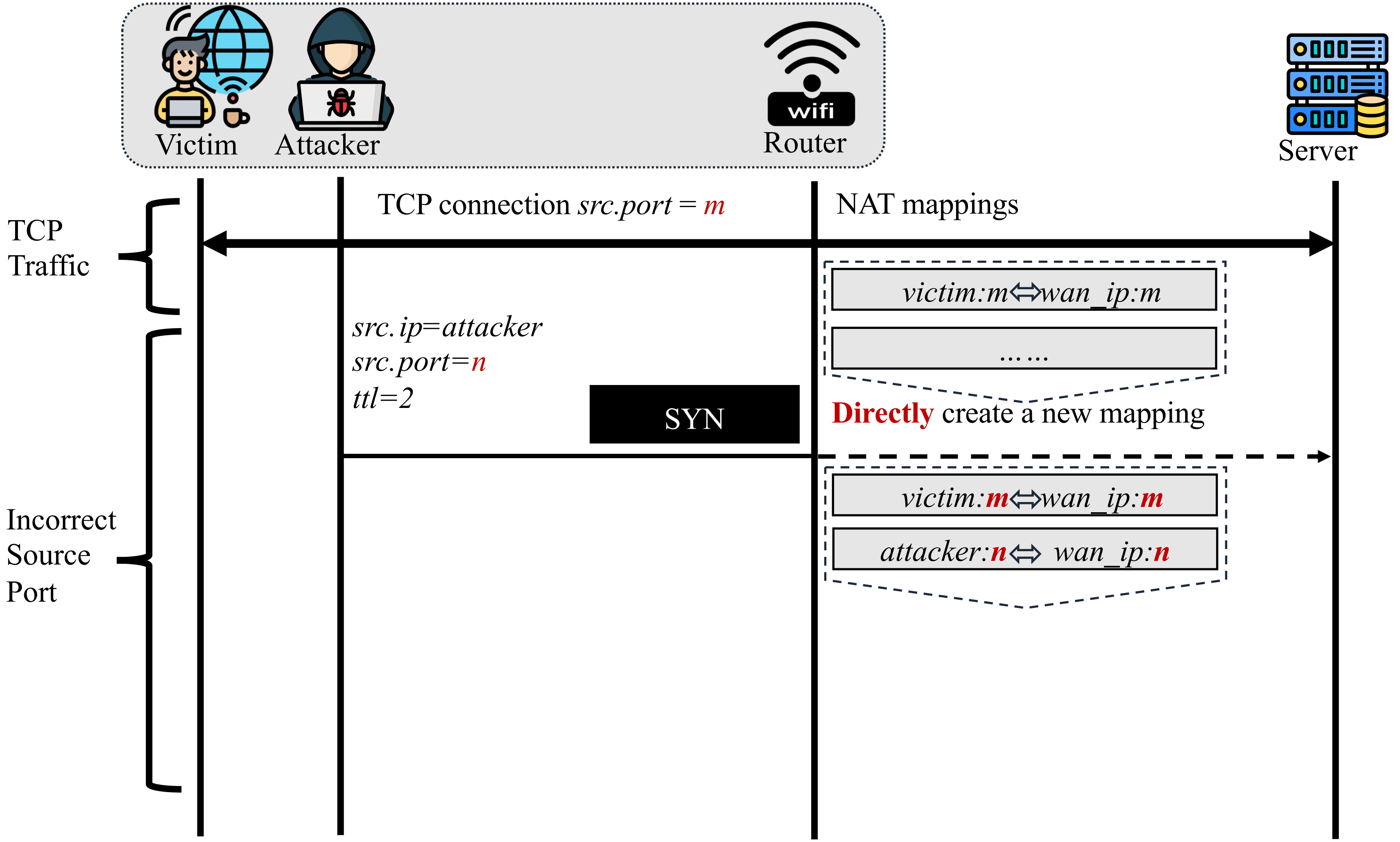


Guess when the source port **has not been used** by the victim.

Making Inferences about Active Connections



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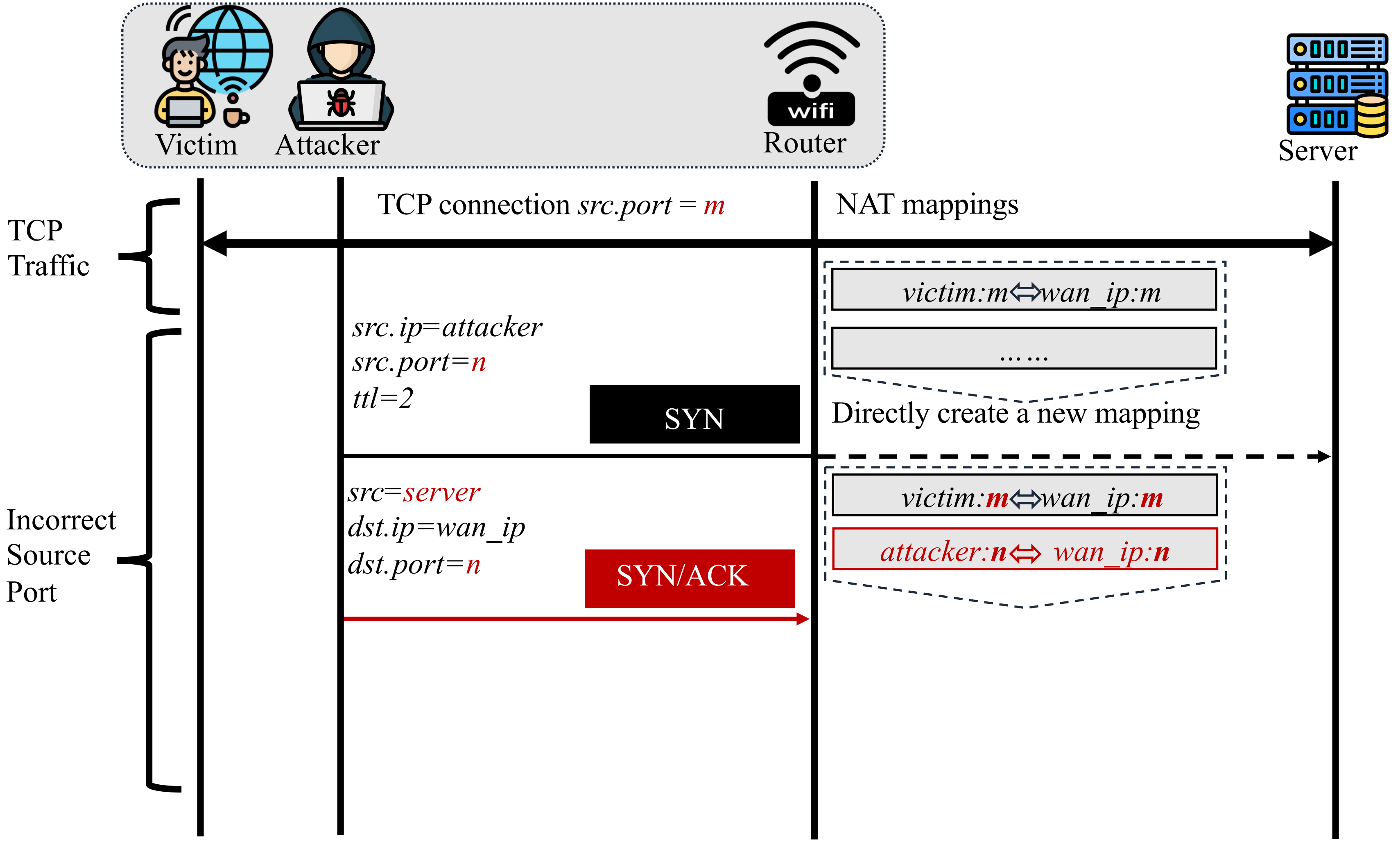

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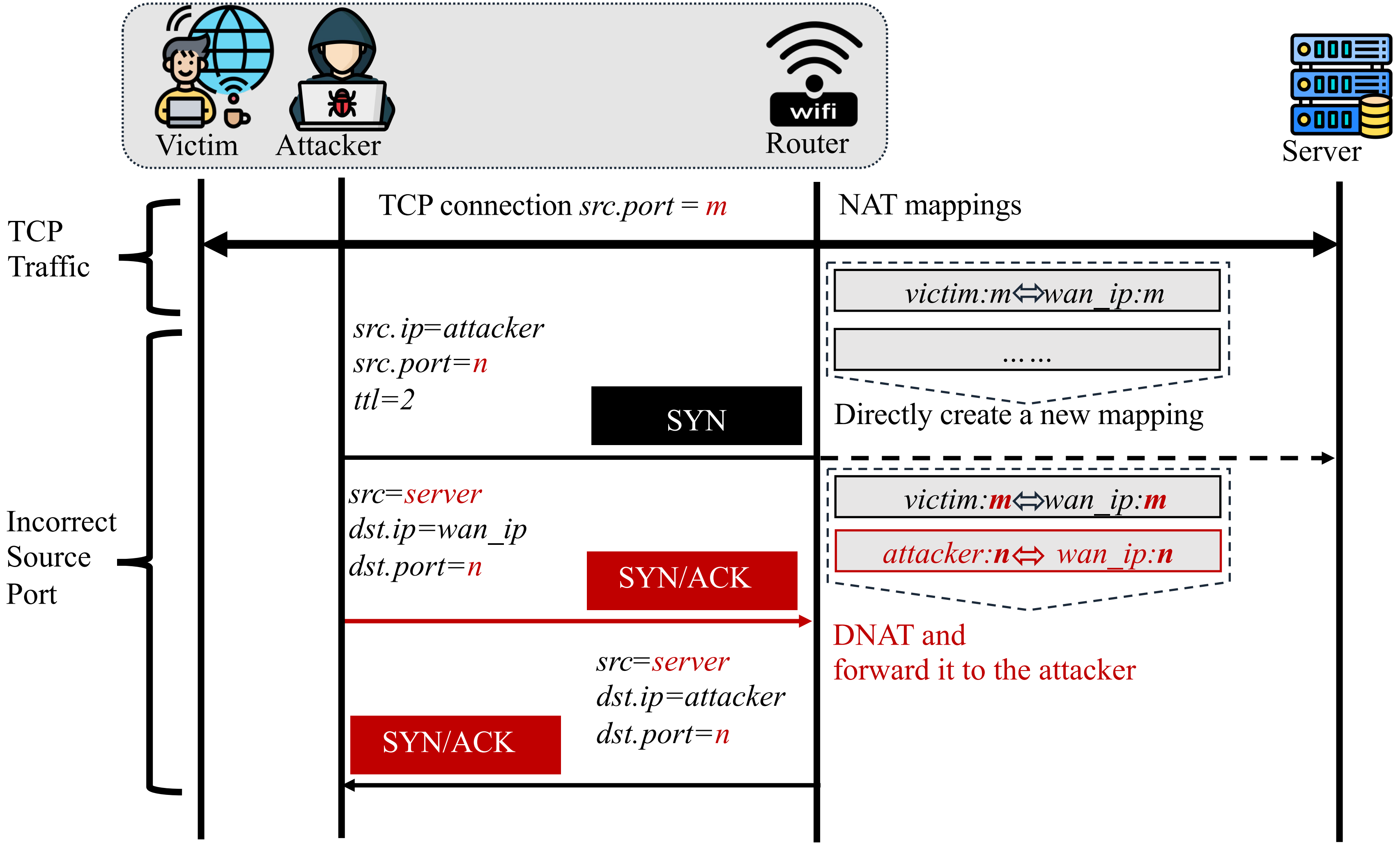

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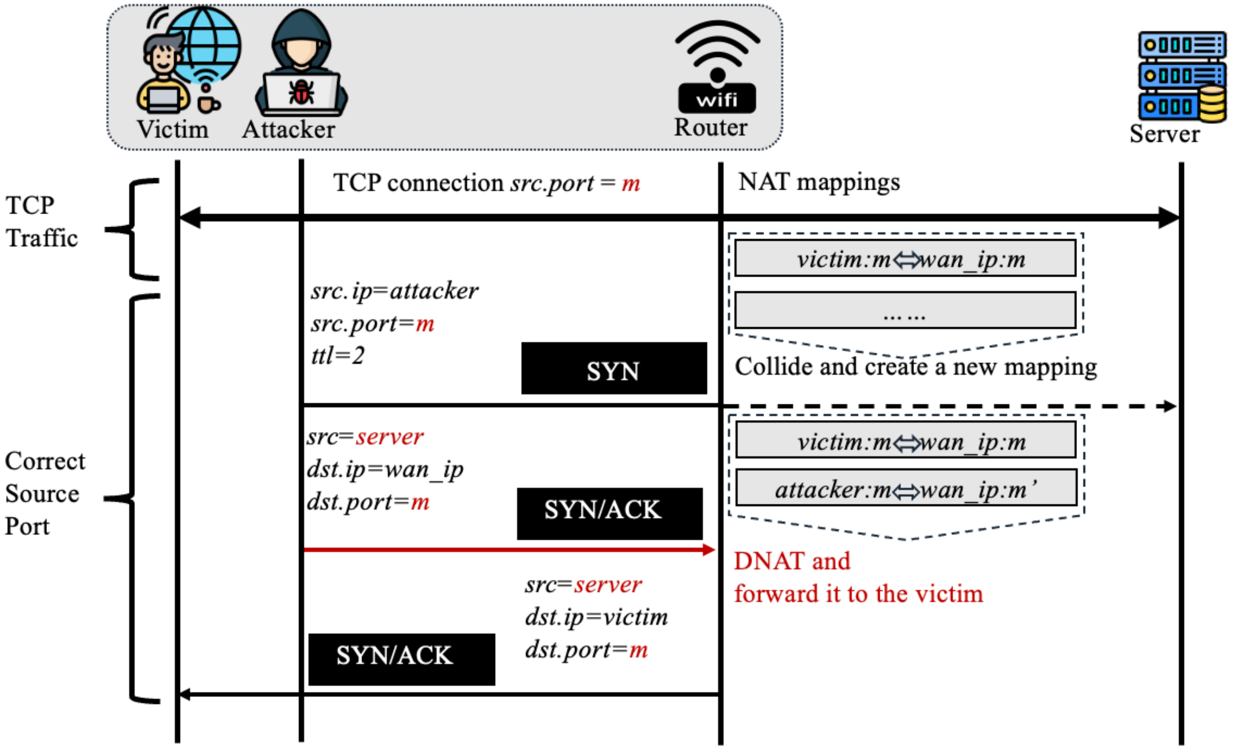


Victim

Attacker

Router

Server

TCP Traffic

TCP connection *src.port* = *m*

NAT mappings

victim:m⇔wan_ip:m

……

src.ip=attacker
src.port=m
ttl=2

SYN

Collide and create a new mapping

Correct Source Port

src=server
dst.ip=wan_ip
dst.port=m

SYN/ACK

victim:m⇔wan_ip:m

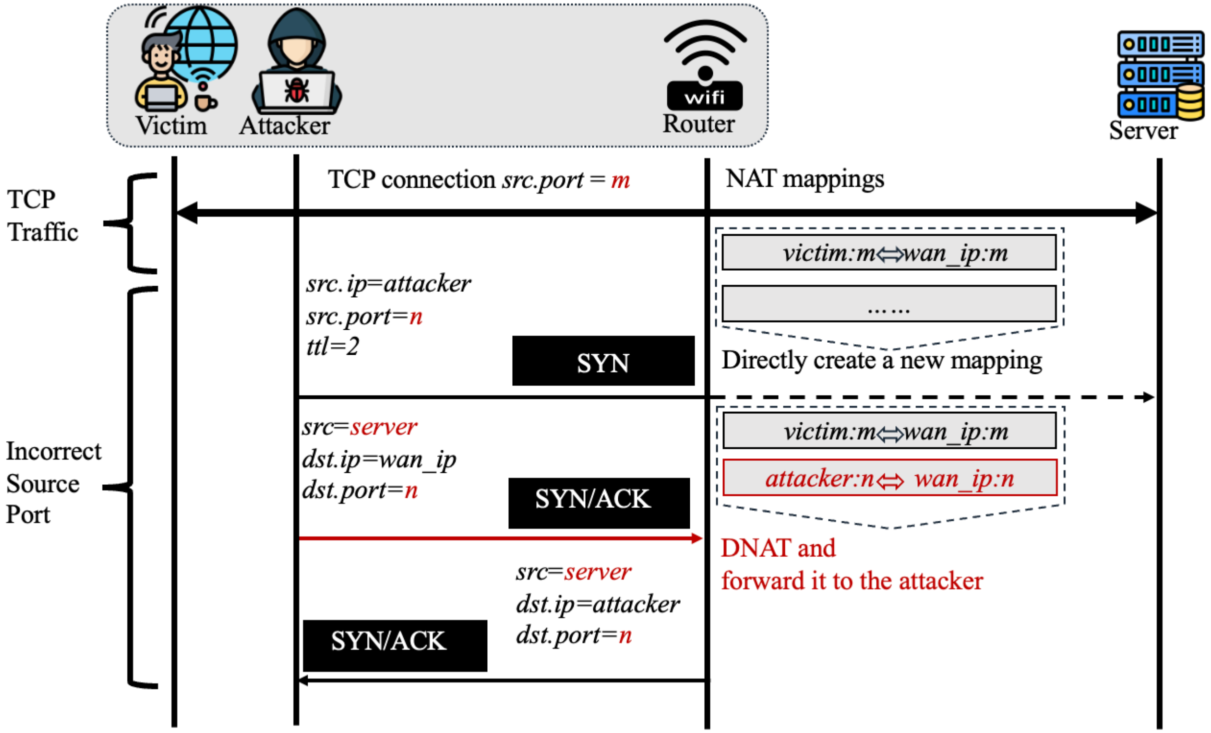
attacker:m⇔wan_ip:m’

DNAT and
forward it to the victim

src=server
dst.ip=victim
dst.port=m

SYN/ACK

Guess when the source port is **used**



Victim

Attacker

Router

Server

TCP Traffic

TCP connection *src.port* = *m*

NAT mappings

victim:m⇔wan_ip:m

……

src.ip=attacker
src.port=n
ttl=2

SYN

Directly create a new mapping

Incorrect Source Port

src=server
dst.ip=wan_ip
dst.port=n

SYN/ACK

victim:m⇔wan_ip:m

attacker:n⇔ wan_ip:n

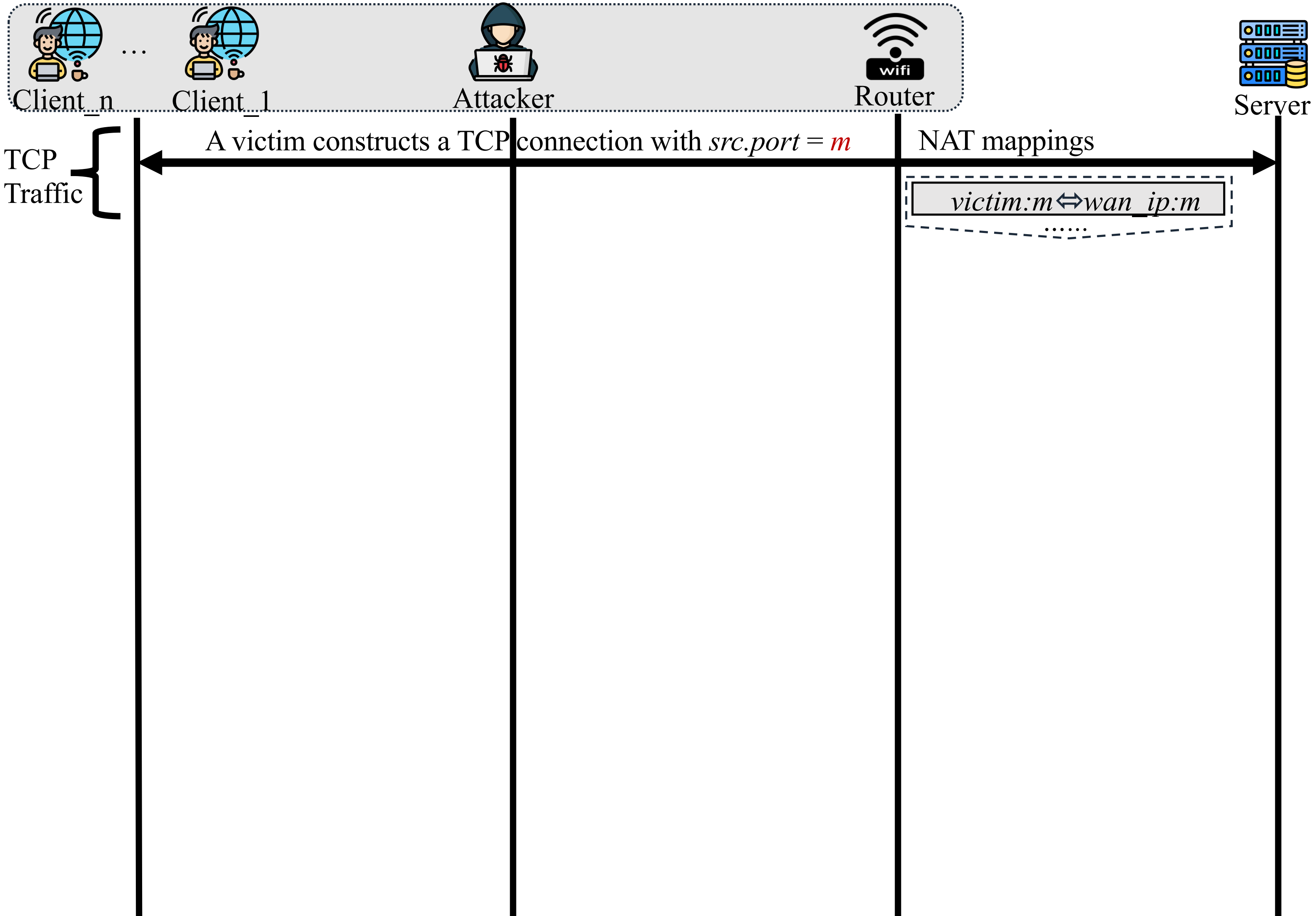
DNAT and
forward it to the attacker

src=server
dst.ip=attacker
dst.port=n

SYN/ACK

Guess when the source port is **not used**

Hijacking Active Connections



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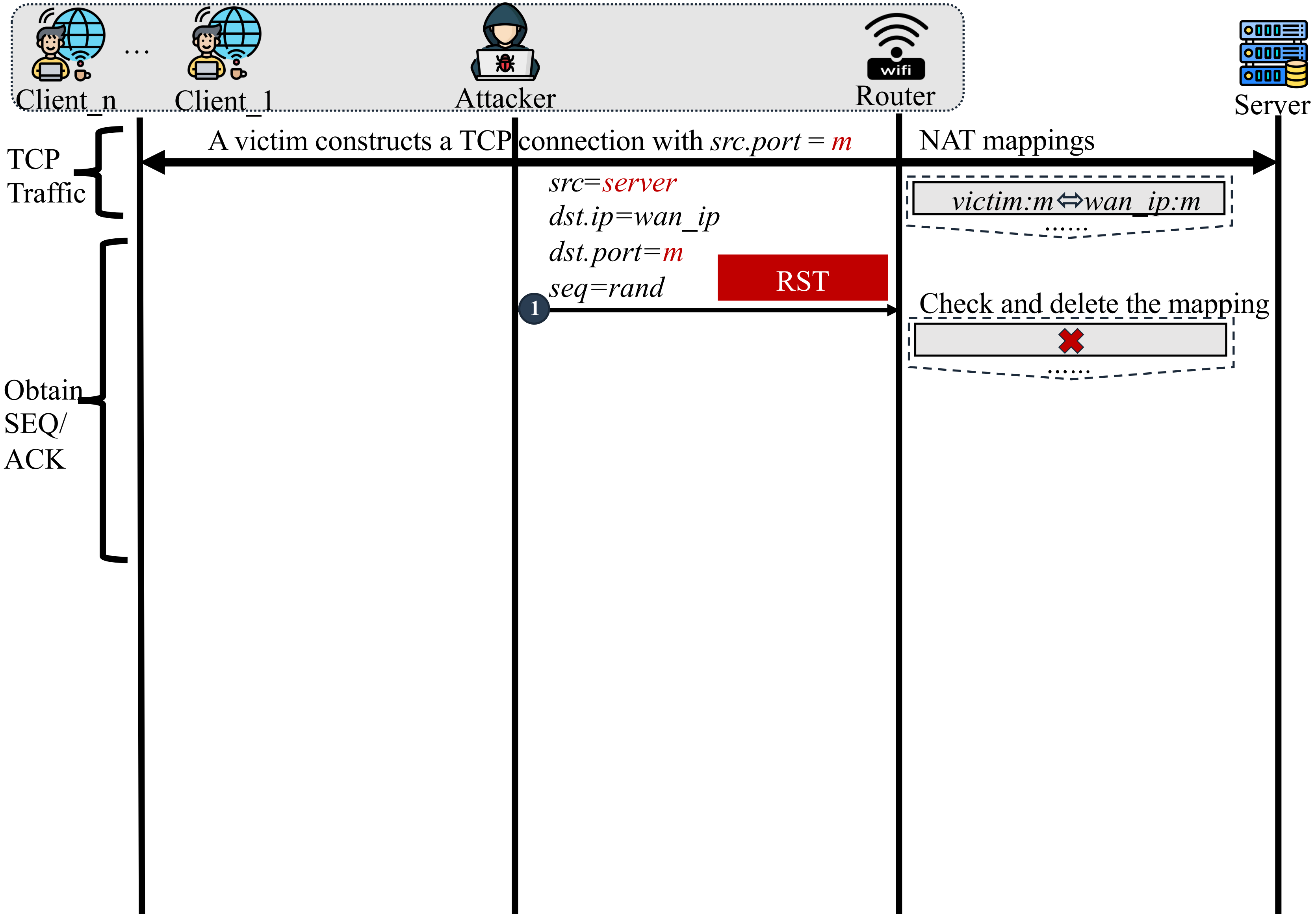

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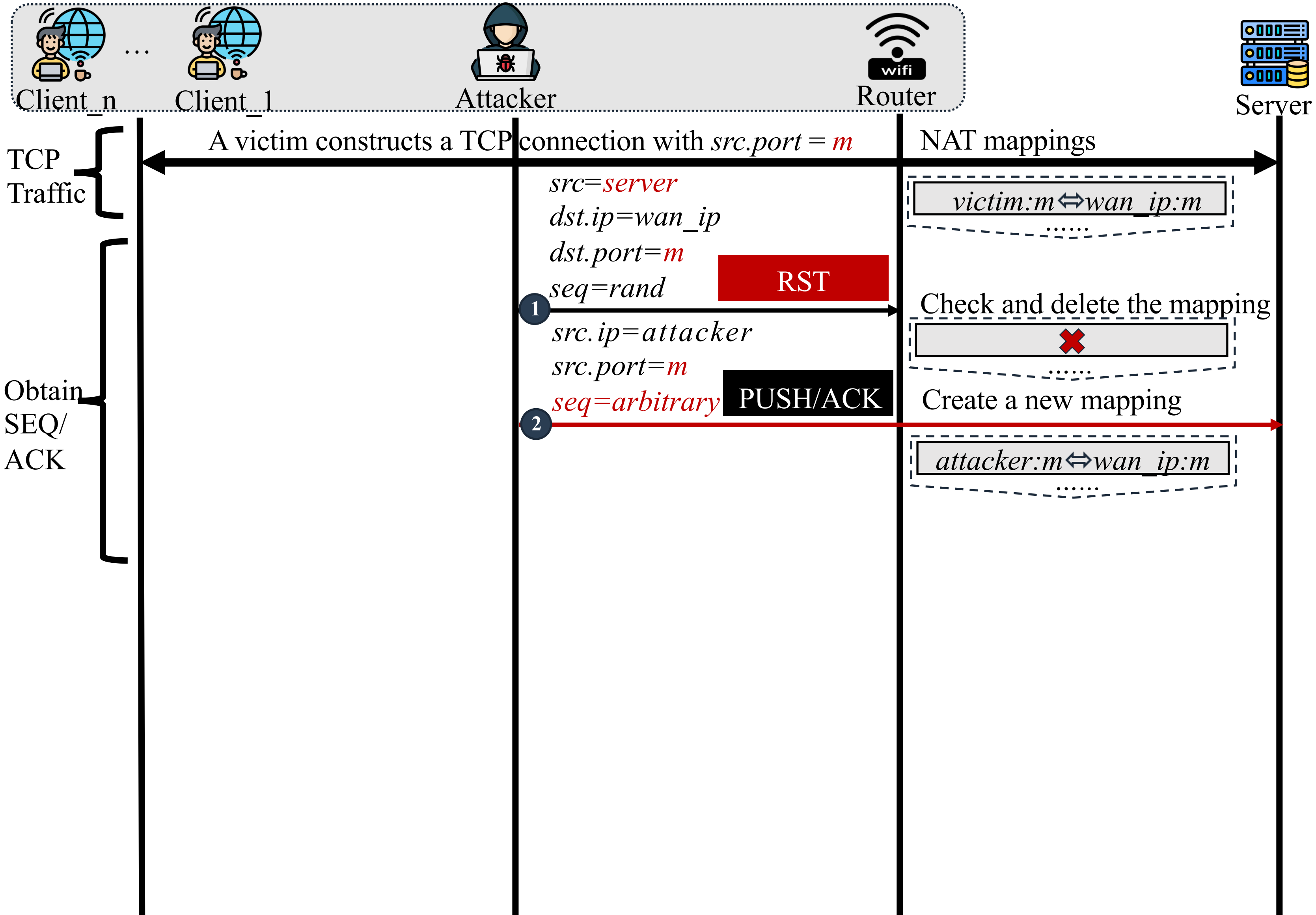

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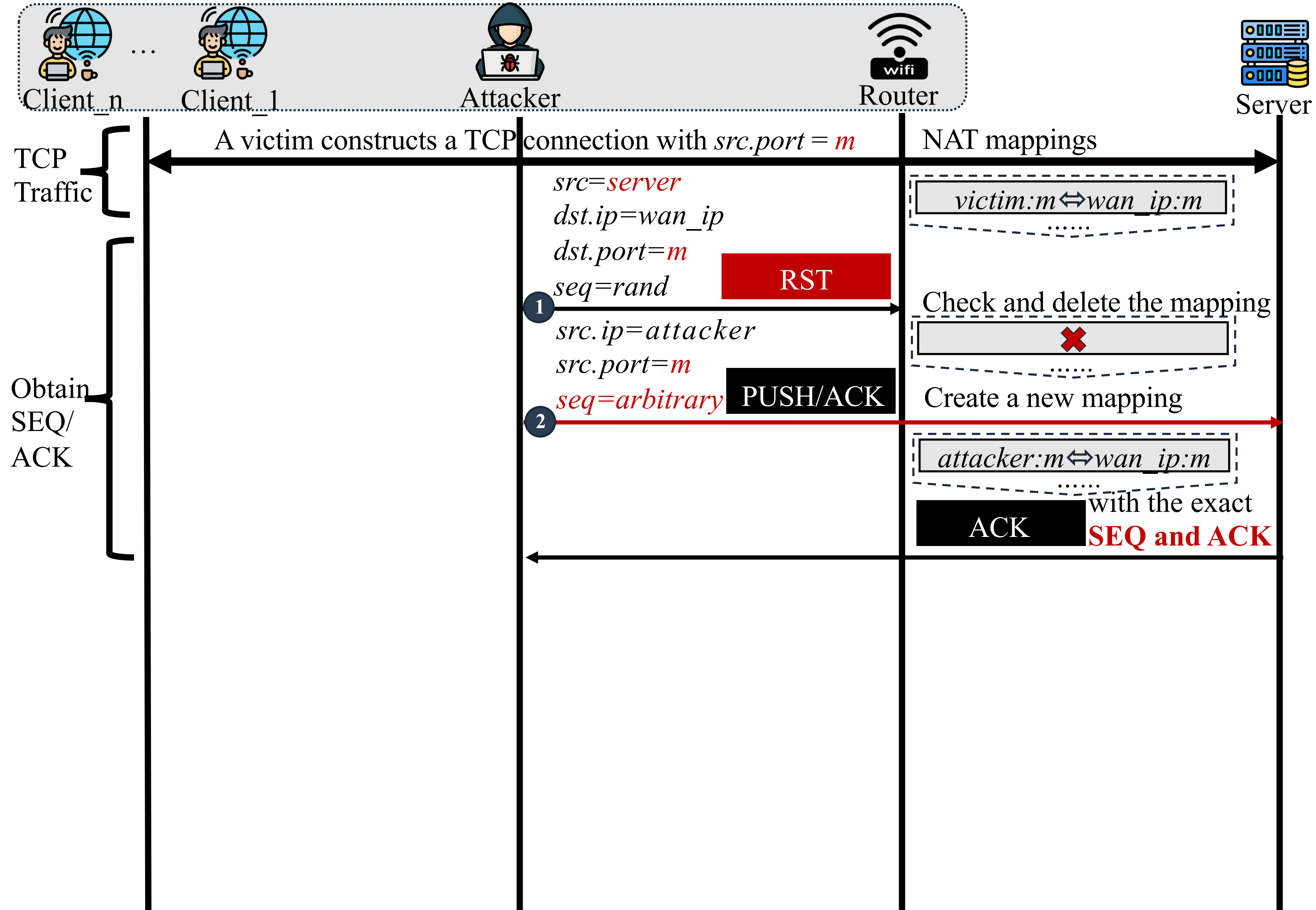

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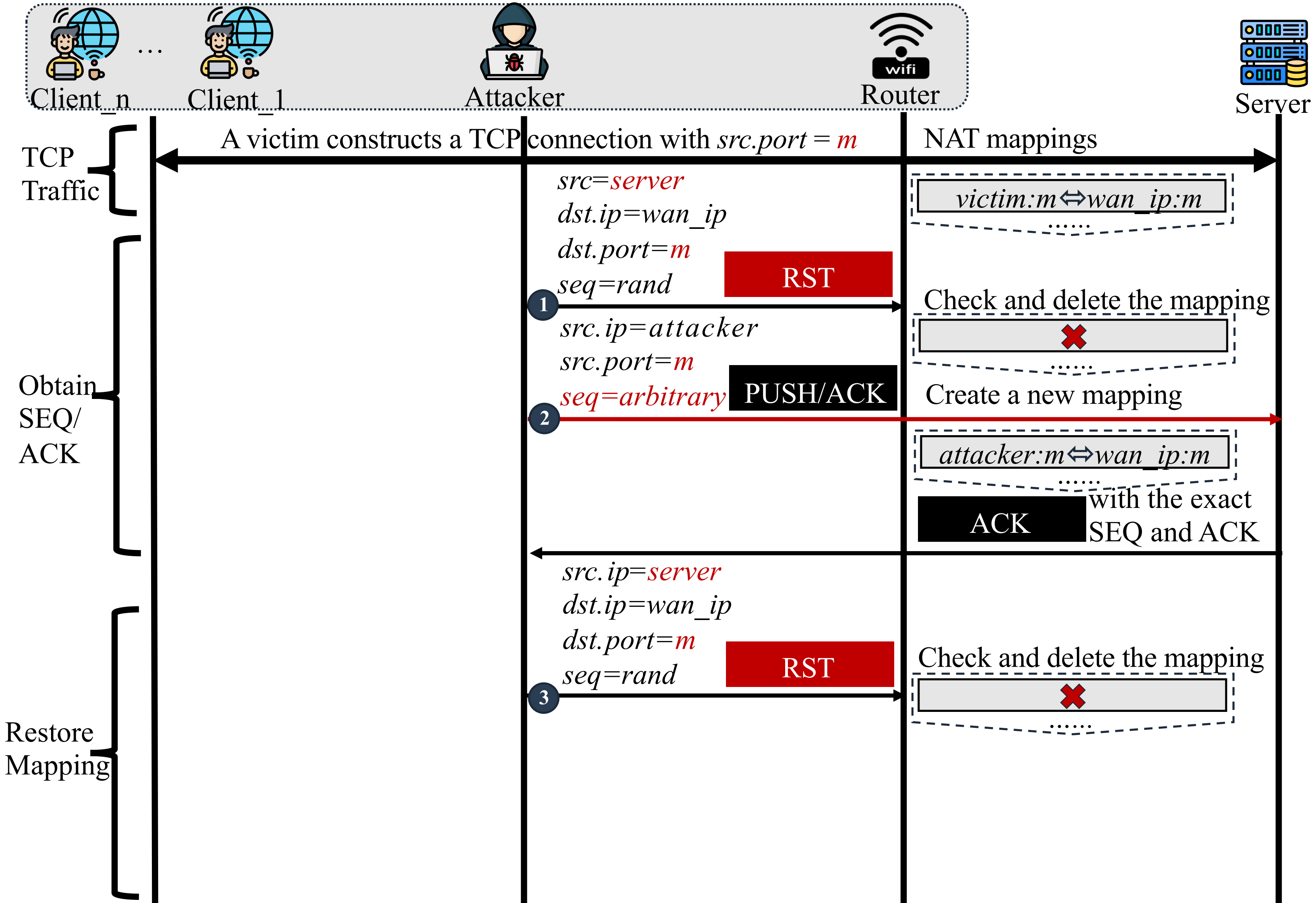

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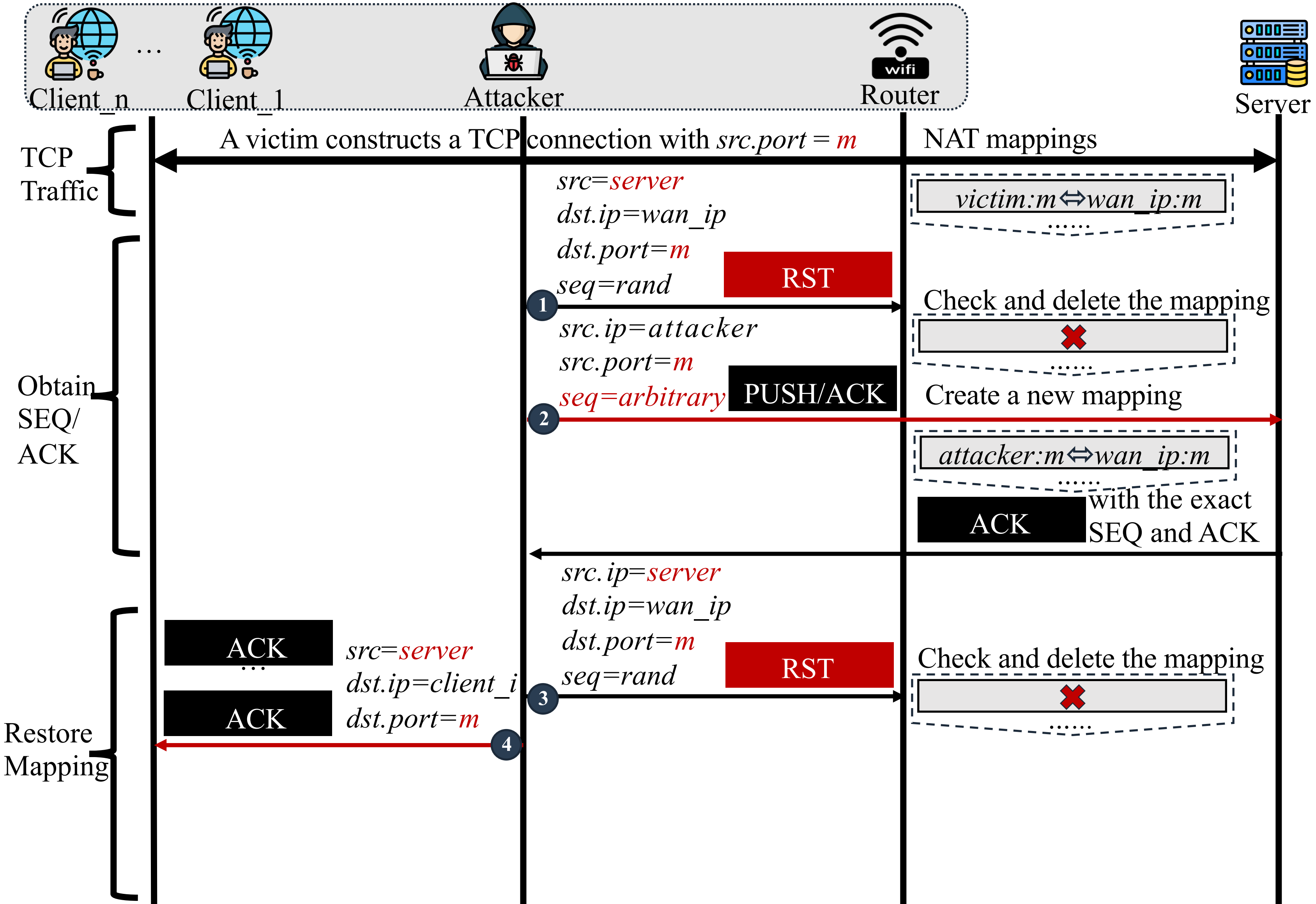

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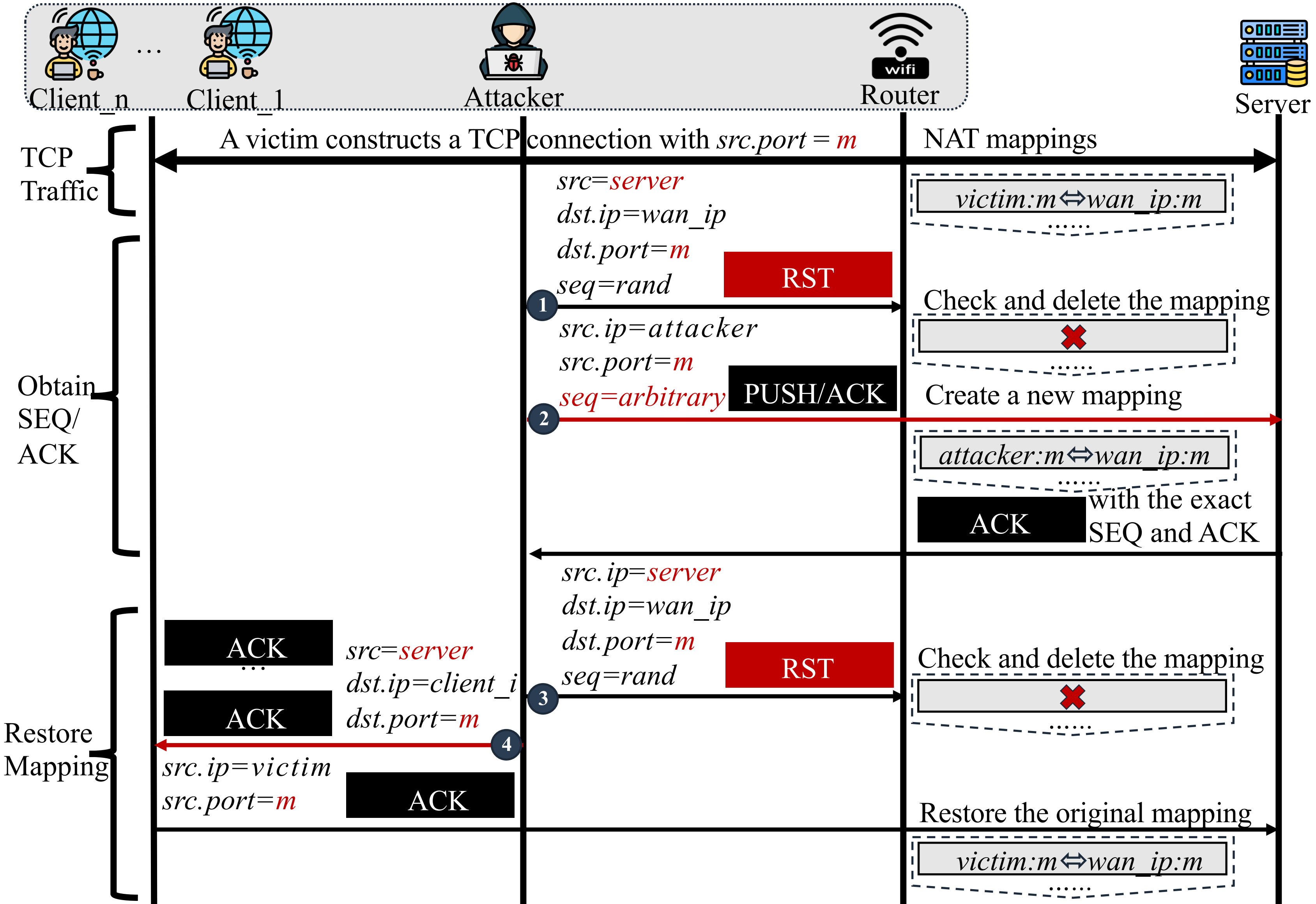
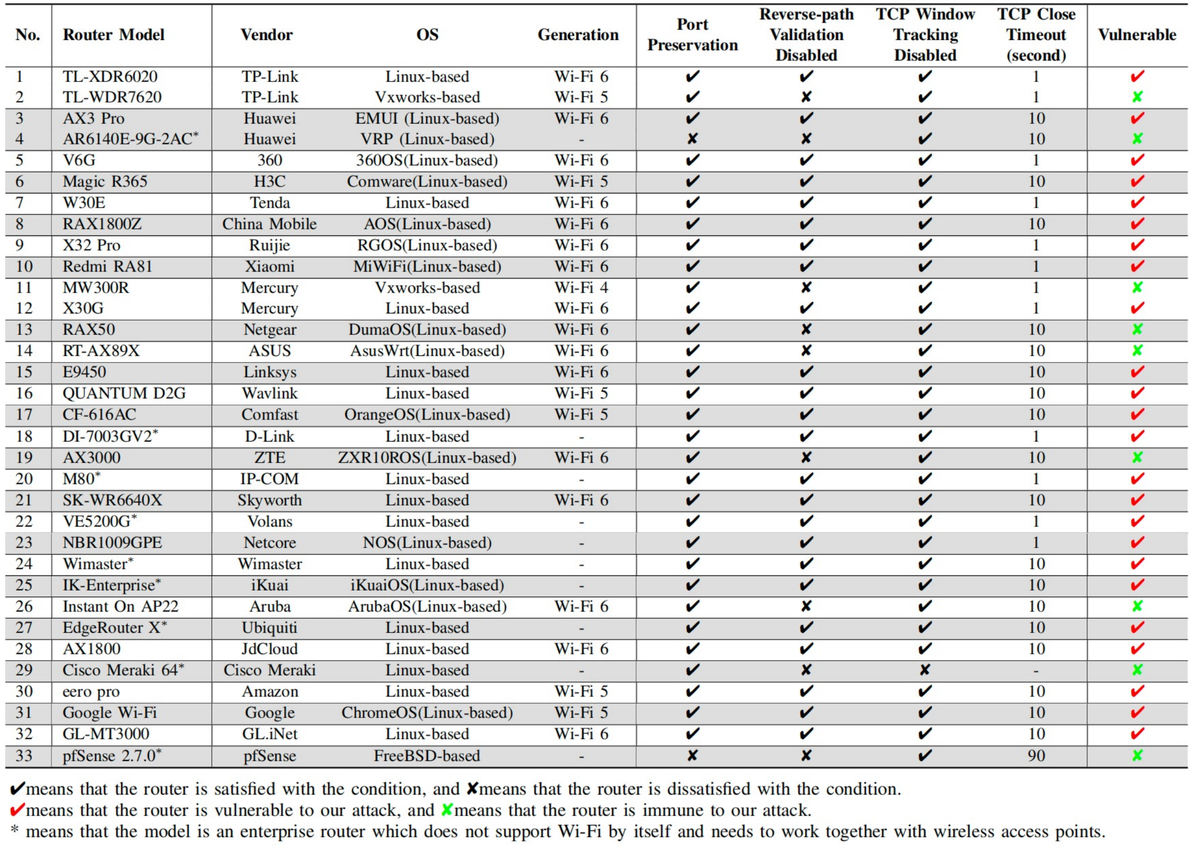


Empirical Study

Analysis of Routers

✎ **We perform tests on 67 mainstream router models (acting as the gateway to provide Internet services) from 30 vendors.**

- 360, Aruba, ASUS, Amazon, Cisco Meraki
- China Mobile, Comfast, D-Link, GL.iNet
- Google, H3C, Huawei, IP-COM, iKuai
- JdCloud, Linksys, Mercury, Netgear, Netcore
- Ruijie, Skyworth, Tenda, TP-Link, Ubiquiti
- Volans, Wavlink, WiMaster, Xiaomi, and ZTE



No.	Router Model	Vendor	OS	Generation	Port Preservation	Reverse-path Validation Disabled	TCP Window Tracking Disabled	TCP Close Timeout (second)	Vulnerable
1	TL-XDR6020	TP-Link	Linux-based	Wi-Fi 6	✔	✔	✔	1	✔
2	TL-WDR7620	TP-Link	Vxworks-based	Wi-Fi 5	✔	✘	✔	1	✘
3	AX3 Pro	Huawei	EMUI (Linux-based)	Wi-Fi 6	✔	✔	✔	10	✔
4	AR6140E-9G-2AC*	Huawei	VRP (Linux-based)	-	✘	✘	✔	10	✘
5	V6G	360	360OS(Linux-based)	Wi-Fi 6	✔	✔	✔	1	✔
6	Magic R365	H3C	Comware(Linux-based)	Wi-Fi 5	✔	✔	✔	10	✔
7	W30E	Tenda	Linux-based	Wi-Fi 6	✔	✔	✔	1	✔
8	RAX1800Z	China Mobile	AOS(Linux-based)	Wi-Fi 6	✔	✔	✔	10	✔
9	X32 Pro	Ruijie	RGOS(Linux-based)	Wi-Fi 6	✔	✔	✔	1	✔
10	Redmi RA81	Xiaomi	MiWiFi(Linux-based)	Wi-Fi 6	✔	✔	✔	1	✔
11	MW300R	Mercury	Vxworks-based	Wi-Fi 4	✔	✘	✔	1	✘
12	X30G	Mercury	Linux-based	Wi-Fi 6	✔	✔	✔	1	✔
13	RAX50	Netgear	DumaOS(Linux-based)	Wi-Fi 6	✔	✘	✔	10	✘
14	RT-AX89X	ASUS	AsusWrt(Linux-based)	Wi-Fi 6	✔	✘	✔	10	✘
15	E9450	Linksys	Linux-based	Wi-Fi 6	✔	✔	✔	10	✔
16	QUANTUM D2G	Wavlink	Linux-based	Wi-Fi 5	✔	✔	✔	10	✔
17	CF-616AC	Comfast	OrangeOS(Linux-based)	Wi-Fi 5	✔	✔	✔	10	✔
18	DI-7003GV2*	D-Link	Linux-based	-	✔	✔	✔	1	✔
19	AX3000	ZTE	ZXR10ROS(Linux-based)	Wi-Fi 6	✔	✘	✔	10	✘
20	M80*	IP-COM	Linux-based	-	✔	✔	✔	1	✔
21	SK-WR6640X	Skyworth	Linux-based	Wi-Fi 6	✔	✔	✔	10	✔
22	VE5200G*	Volans	Linux-based	-	✔	✔	✔	1	✔
23	NBR1009GPE	Netcore	NOS(Linux-based)	-	✔	✔	✔	1	✔
24	Wimaster*	Wimaster	Linux-based	-	✔	✔	✔	10	✔
25	IK-Enterprise*	iKuai	iKuaiOS(Linux-based)	-	✔	✔	✔	10	✔
26	Instant On AP22	Aruba	ArubaOS(Linux-based)	Wi-Fi 6	✔	✘	✔	10	✘
27	EdgeRouter X*	Ubiquiti	Linux-based	-	✔	✔	✔	10	✔
28	AX1800	JdCloud	Linux-based	Wi-Fi 6	✔	✔	✔	10	✔
29	Cisco Meraki 64*	Cisco Meraki	Linux-based	-	✔	✘	✘	-	✘
30	eero pro	Amazon	Linux-based	Wi-Fi 5	✔	✔	✔	10	✔
31	Google Wi-Fi	Google	ChromeOS(Linux-based)	Wi-Fi 5	✔	✔	✔	10	✔
32	GL-MT3000	GL.iNet	Linux-based	Wi-Fi 6	✔	✔	✔	10	✔
33	pfSense 2.7.0*	pfSense	FreeBSD-based	-	✘	✘	✔	90	✘

✔means that the router is satisfied with the condition, and ✘means that the router is dissatisfied with the condition.
✔means that the router is vulnerable to our attack, and ✘means that the router is immune to our attack.
* means that the model is an enterprise router which does not support Wi-Fi by itself and needs to work together with wireless access points.

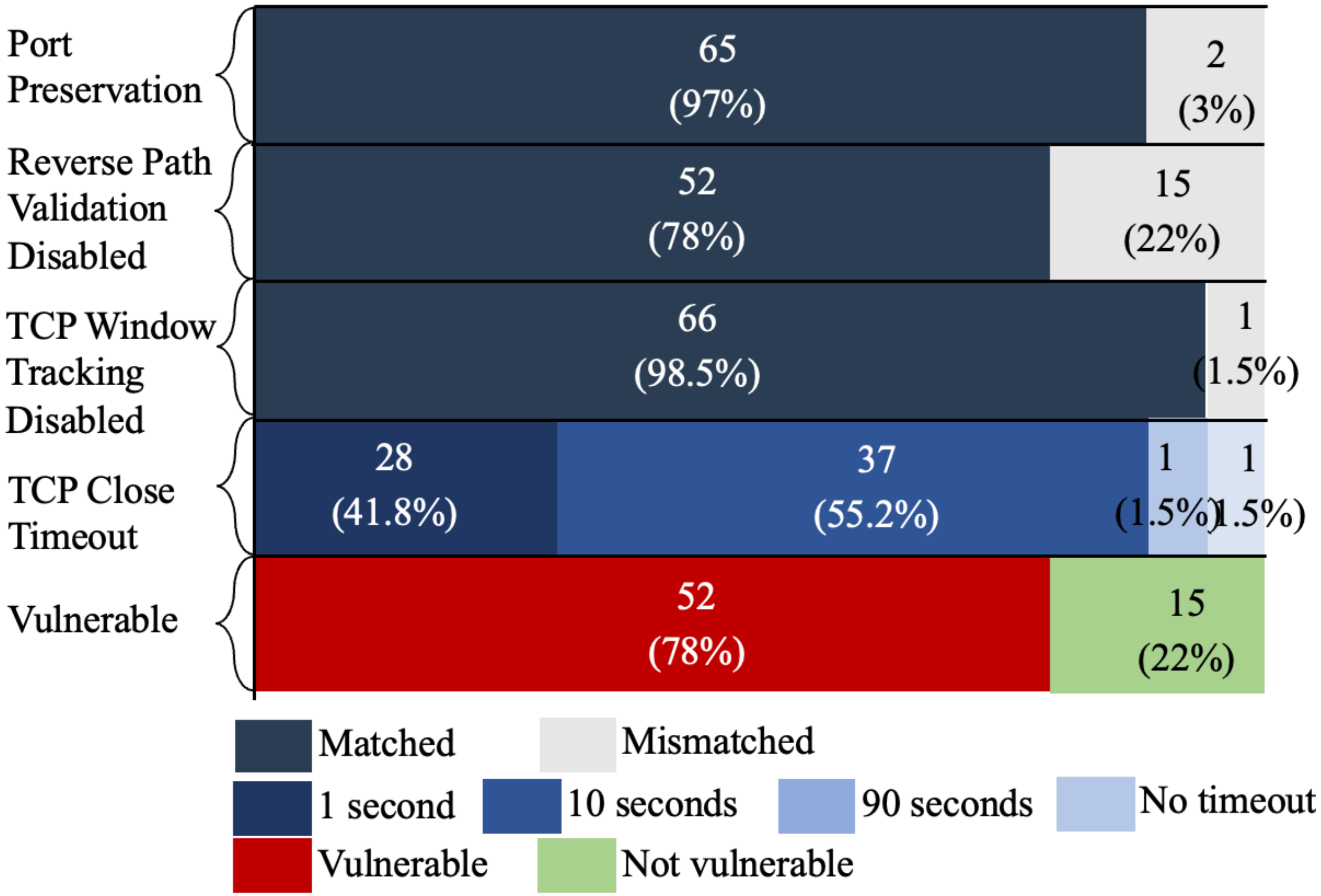
Test Results of the Router Models.

Analysis of Routers

✎ 52 of the 67 tested routers are vulnerable.

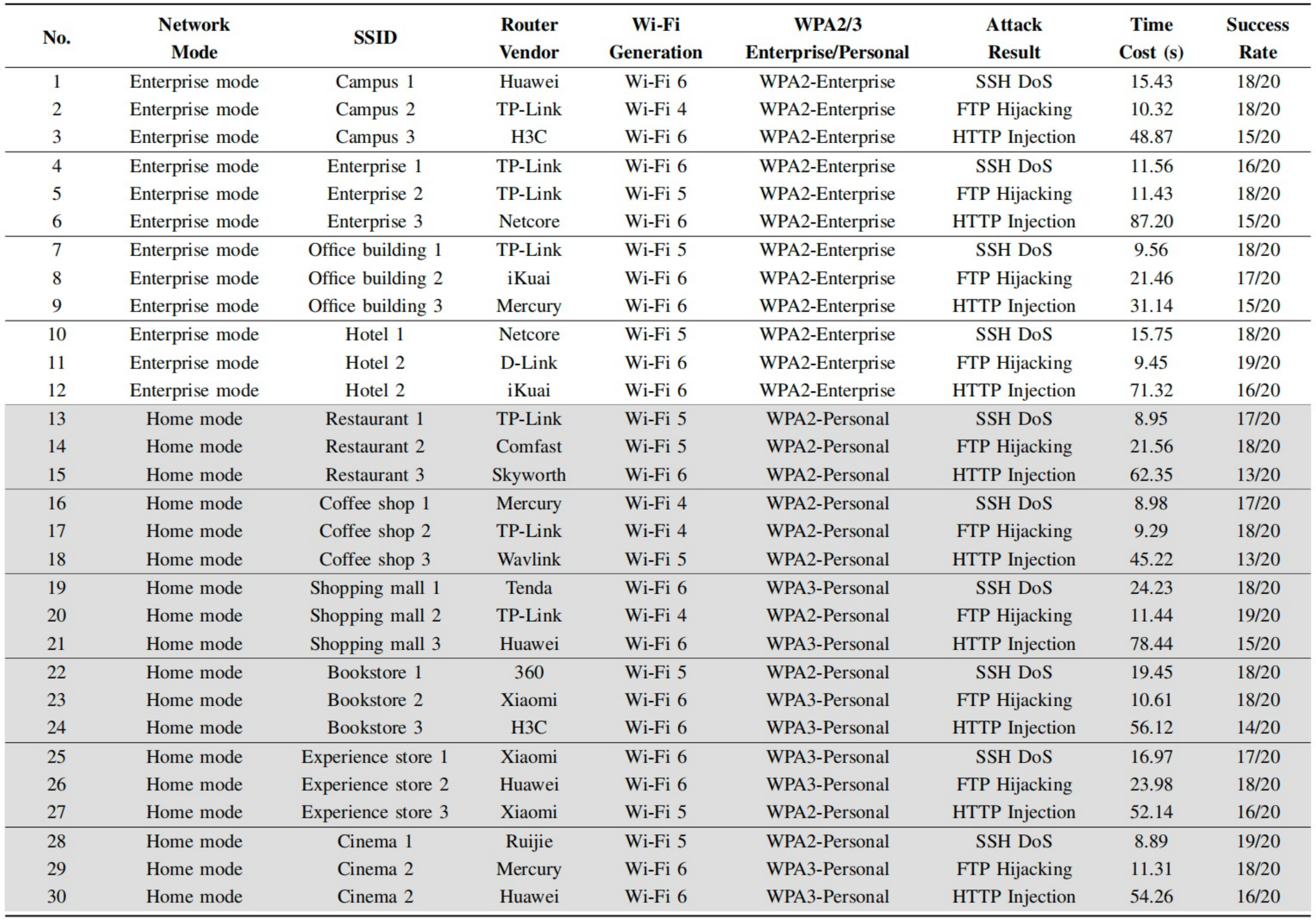
✎ 15 models are immune to the attack as they do not fulfill all of the conditions.

✎ The vulnerable routers are from 24 of the 30 vendors.



Attack Evaluation

- We conduct thorough experiments of the attack in **93 various Wi-Fi** networks.
- We take three case studies of attacks on **SSH, FTP, and HTTP** applications and measuring the time cost and success rate of each attack.



No.	Network Mode	SSID	Router Vendor	Wi-Fi Generation	WPA2/3 Enterprise/Personal	Attack Result	Time Cost (s)	Success Rate
1	Enterprise mode	Campus 1	Huawei	Wi-Fi 6	WPA2-Enterprise	SSH DoS	15.43	18/20
2	Enterprise mode	Campus 2	TP-Link	Wi-Fi 4	WPA2-Enterprise	FTP Hijacking	10.32	18/20
3	Enterprise mode	Campus 3	H3C	Wi-Fi 6	WPA2-Enterprise	HTTP Injection	48.87	15/20
4	Enterprise mode	Enterprise 1	TP-Link	Wi-Fi 6	WPA2-Enterprise	SSH DoS	11.56	16/20
5	Enterprise mode	Enterprise 2	TP-Link	Wi-Fi 5	WPA2-Enterprise	FTP Hijacking	11.43	18/20
6	Enterprise mode	Enterprise 3	Netcore	Wi-Fi 6	WPA2-Enterprise	HTTP Injection	87.20	15/20
7	Enterprise mode	Office building 1	TP-Link	Wi-Fi 5	WPA2-Enterprise	SSH DoS	9.56	18/20
8	Enterprise mode	Office building 2	iKuai	Wi-Fi 6	WPA2-Enterprise	FTP Hijacking	21.46	17/20
9	Enterprise mode	Office building 3	Mercury	Wi-Fi 6	WPA2-Enterprise	HTTP Injection	31.14	15/20
10	Enterprise mode	Hotel 1	Netcore	Wi-Fi 5	WPA2-Enterprise	SSH DoS	15.75	18/20
11	Enterprise mode	Hotel 2	D-Link	Wi-Fi 6	WPA2-Enterprise	FTP Hijacking	9.45	19/20
12	Enterprise mode	Hotel 2	iKuai	Wi-Fi 6	WPA2-Enterprise	HTTP Injection	71.32	16/20
13	Home mode	Restaurant 1	TP-Link	Wi-Fi 5	WPA2-Personal	SSH DoS	8.95	17/20
14	Home mode	Restaurant 2	Comfast	Wi-Fi 5	WPA2-Personal	FTP Hijacking	21.56	18/20
15	Home mode	Restaurant 3	Skyworth	Wi-Fi 6	WPA2-Personal	HTTP Injection	62.35	13/20
16	Home mode	Coffee shop 1	Mercury	Wi-Fi 4	WPA2-Personal	SSH DoS	8.98	17/20
17	Home mode	Coffee shop 2	TP-Link	Wi-Fi 4	WPA2-Personal	FTP Hijacking	9.29	18/20
18	Home mode	Coffee shop 3	Wavlink	Wi-Fi 5	WPA2-Personal	HTTP Injection	45.22	13/20
19	Home mode	Shopping mall 1	Tenda	Wi-Fi 6	WPA3-Personal	SSH DoS	24.23	18/20
20	Home mode	Shopping mall 2	TP-Link	Wi-Fi 4	WPA2-Personal	FTP Hijacking	11.44	19/20
21	Home mode	Shopping mall 3	Huawei	Wi-Fi 6	WPA3-Personal	HTTP Injection	78.44	15/20
22	Home mode	Bookstore 1	360	Wi-Fi 5	WPA2-Personal	SSH DoS	19.45	18/20
23	Home mode	Bookstore 2	Xiaomi	Wi-Fi 6	WPA3-Personal	FTP Hijacking	10.61	18/20
24	Home mode	Bookstore 3	H3C	Wi-Fi 6	WPA3-Personal	HTTP Injection	56.12	14/20
25	Home mode	Experience store 1	Xiaomi	Wi-Fi 6	WPA3-Personal	SSH DoS	16.97	17/20
26	Home mode	Experience store 2	Huawei	Wi-Fi 6	WPA3-Personal	FTP Hijacking	23.98	18/20
27	Home mode	Experience store 3	Xiaomi	Wi-Fi 5	WPA2-Personal	HTTP Injection	52.14	16/20
28	Home mode	Cinema 1	Ruijie	Wi-Fi 5	WPA2-Personal	SSH DoS	8.89	19/20
29	Home mode	Cinema 2	Mercury	Wi-Fi 6	WPA3-Personal	FTP Hijacking	11.31	18/20
30	Home mode	Cinema 2	Huawei	Wi-Fi 6	WPA3-Personal	HTTP Injection	54.26	16/20

Experimental Results of TCP Attacks in the Wi-Fi Networks.

Attack Evaluation

SSH DoS Attack:

- Success rate: 87.4%
- Attack time: ~17.5s

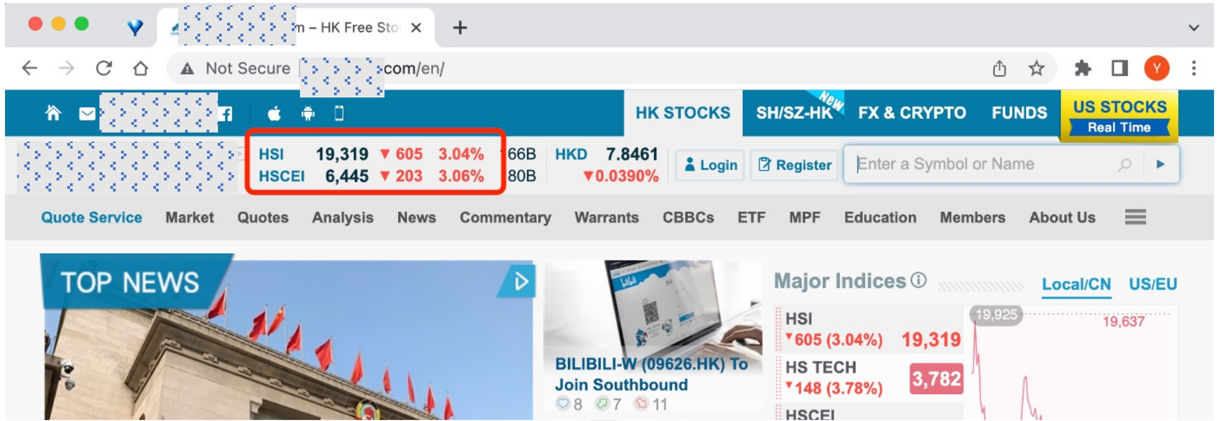
FTP Hijacking Attack:

- Success rate: 82.6%
- Attack time: ~19.4s

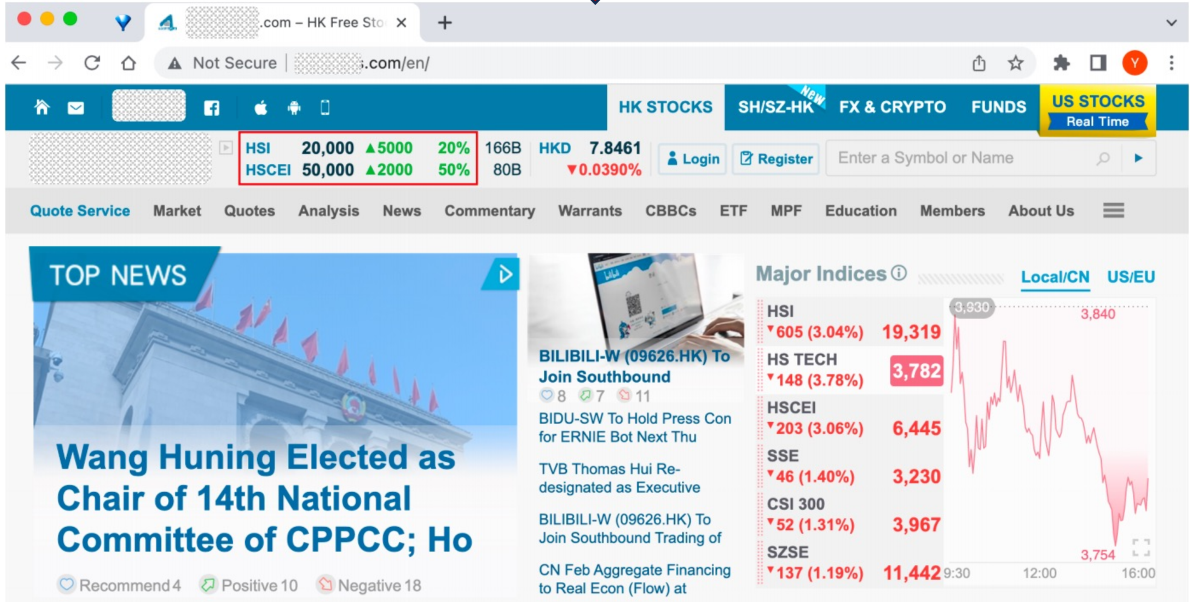
HTTP Injection Attack:

- Success rate: 76.1%
- Attack time: ~54.5s

Attack	Inferring	Getting	Finishing	Total	BW	Success
Type	Port(s)	SEQ/ACK(s)	Attacking(s)	Time(s)	(pkts)	Rate
SSH DoS	8.1	8.4	1.0	17.5	4000	87.4%
FTP Hijacking	9.1	9.2	1.1	19.4	4000	82.6%
HTTP Injection	9.4	15.2	29.9	54.5	4000	76.1%



After attack



Wang Huning Elected as Chair of 14th National Committee of CPPCC; Ho

BILIBILI-W (09626.HK) To Join Southbound

BIDU-SW To Hold Press Con for ERNIE Bot Next Thu

TVB Thomas Hui Re-designated as Executive

BILIBILI-W (09626.HK) To Join Southbound Trading of

CN Feb Aggregate Financing to Real Econ (Flow) at

Disclosure and Mitigation

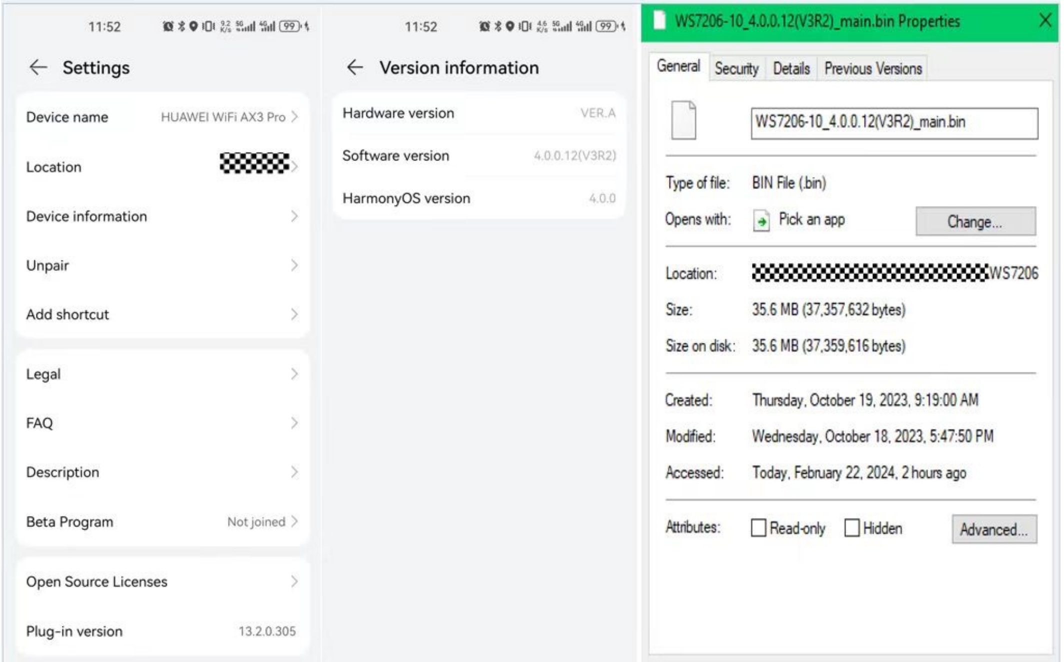
Disclosure and Mitigation

✎ Ethical disclosure:

- Acknowledgment from the **OpenWrt** community and **7 router vendors** (i.e., TP-Link, Huawei, Xiaomi, 360, Mercury, Ubiquiti, and Linksys)
- Some vendors have released patches to fix this vulnerability, e.g., **OpenWrt, Huawei …**
- **10 CVEs** (from CVE-2023-30305 to CVE-2023-30314)

✎ Mitigation :

- Take random port allocation method
- Enable reverse path validation
- Enable TCP window tracking



11:52

← Settings

Device name	HUAWEI WiFi AX3 Pro >
Location	[redacted] >
Device information	>
Unpair	>
Add shortcut	>
Legal	>
FAQ	>
Description	>
Beta Program	Not joined >
Open Source Licenses	>
Plug-in version	13.2.0.305

11:52

← Version information

Hardware version	VER.A
Software version	4.0.0.12(V3R2)
HarmonyOS version	4.0.0

WS7206-10_4.0.0.12(V3R2)_main.bin Properties

WS7206-10_4.0.0.12(V3R2)_main.bin

Type of file: BIN File (.bin)

Opens with: Pick an app

Location: [redacted]WS7206

Size: 35.6 MB (37,357,632 bytes)

Size on disk: 35.6 MB (37,359,616 bytes)

Created: Thursday, October 19, 2023, 9:19:00 AM

Modified: Wednesday, October 18, 2023, 5:47:50 PM

Accessed: Today, February 22, 2024, 2 hours ago

Attributes: □ Read-only □ Hidden

The Patch from Huawei Developers

Conclusion

✐Uncovered a new NAT vulnerability in Wi-Fi networks to **attack TCP connections**.

✐Performed large-scale **measurements** of routers and **experiments** in real networks.

✐Suggested **defense countermeasures** and some of them have been adopted.

Questions?