FrostyGoop's Zoom-In: A Closer Look into the Malware Artifacts, Behaviors and Network Communications

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Executive Summary

In July 2024, the operational technology (OT)-centric malware FrostyGoop/BUSTLEBERM became publicly known, after attackers used it to disrupt critical infrastructure. The outage occurred after the Cyber Security Situation Center (CSSC), affiliated with the Security Service of Ukraine, disclosed details [PDF] of an attack on a municipal energy company in Ukraine in early 2024.

FrostyGoop is the ninth reported OT-centric malware, but the first that used Modbus TCP communications to impact the power supply to heating services for over 600 apartment buildings. FrostyGoop can be used both within a compromised perimeter and externally if the target device is accessible over the internet. FrostyGoop sends Modbus commands to read or modify data on industrial control systems (ICS) devices, causing damage to the environment where attackers installed it.

Based on this reporting, we conducted a deeper analysis and uncovered new samples of FrostyGoop and other related indicators. These new indicators include configuration files and libraries used by the malware, as well as artifacts associated with an infection. We also investigate network communications and provide new insights based on open-source intelligence (OSINT) data and our own telemetry.

OT malware is an increasing concern of security professionals across the globe, and FrostyGoop provides a notable case study of this growing threat.

Palo Alto Networks customers are better protected from the threats discussed in this article through our products and services such as the following:

- Industrial OT Security
- Information provided by Palo Alto Networks Next-Generation Firewall with Advanced Threat Prevention
- Advanced WildFire
- Cortex Xpanse
- Cortex XDR and Cortex XSIAM
- Prisma Cloud

If you think you might have been compromised or have an urgent matter, contact the Unit 42 Incident Response team.

Technical Analysis of FrostyGoop

Attackers employed this malware associated with Russian actors in a cyberattack that caused a two-day heating system outage affecting over 600 apartment buildings in Ukraine, during sub-zero temperatures.

According to an open-source report, attackers made the initial compromise through a vulnerability in a MikroTik router. However, we have not confirmed this delivery method and bad actors might instead have delivered the malware via OT devices exposed to the internet.

FrostyGoop makes use of the Modbus TCP protocol to interact directly with ICS/OT devices, and therefore it is considered an ICS-centric malware. This is the ninth known ICS-centric malware.

In addition, Modbus is one of the most common protocols used in critical infrastructure. During this attack, the adversaries dispatched Modbus commands to ENCO control devices, leading to inaccurate measurements and system malfunctions. Remediating these issues took nearly two days.

Although bad actors used the malware to attack ENCO control devices, the malware can attack any other type of device that speaks Modbus TCP. Our telemetry indicates that 1,088,175 Modbus TCP devices were exposed to the internet from Sept. 2-Oct. 2, 2024, and 6,211,623 devices were exposed overall.

The details needed by FrostyGoop to establish a Modbus TCP connection and send Modbus commands to a targeted ICS device can be provided as command-line arguments or included in a separate JSON configuration file.

Malware Samples Analysis

FrostyGoop is compiled using the Go programming language, sometimes referred to as Golang. The malware uses a relatively obscure open-source Modbus implementation.

Further analysis of the Modbus library revealed this implementation does not natively support supplying arguments using a JSON file, making this a strong identifier for the malware. Moreover, the JSON object structure follows a specific format based on the commands this malware supports. FrostyGoop also contains capabilities for logging the output to a console or to a JSON file.

Attackers can supply two types of parameters to FrostyGoop:

- The first type of parameter consists of the possible operations an attacker can execute toward the registers of a Modbus device
- The second parameter consists of timing configurations.

Figure 1 shows an example of the first type of parameter for an operation using Tasks and Iplist under the register for main::main.TaskList___runtime.structtype_fields.

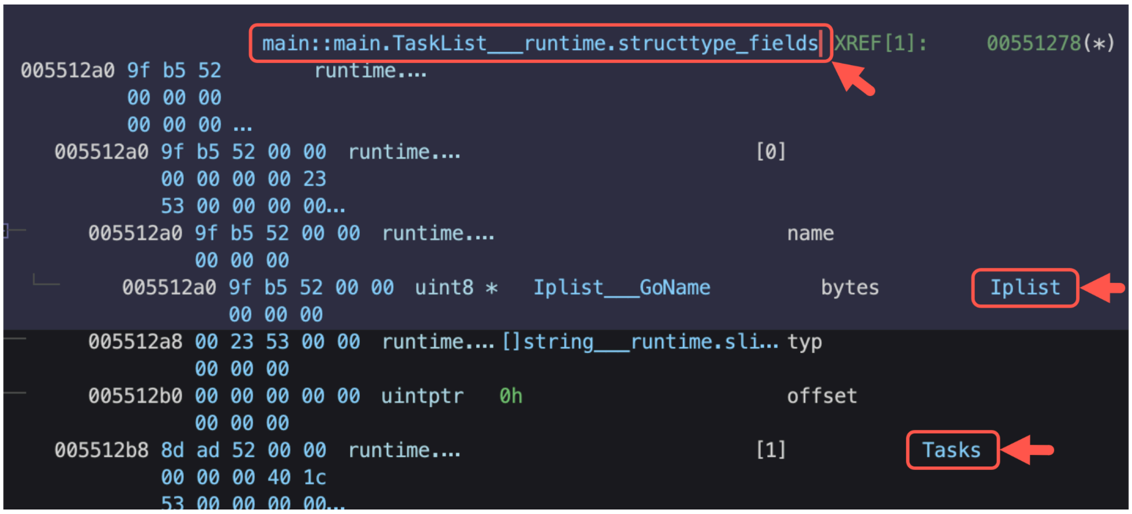


Figure 1. Binary Ninja showing FrostyGoop operations for Tasks and Iplist under the main::main.TaskList___runtime.structtype_fields register.

Figure 2 shows an example of an operation for Code, Address, Count, Value and State under the register for main::main.TaskList___runtime.structtype_fields.

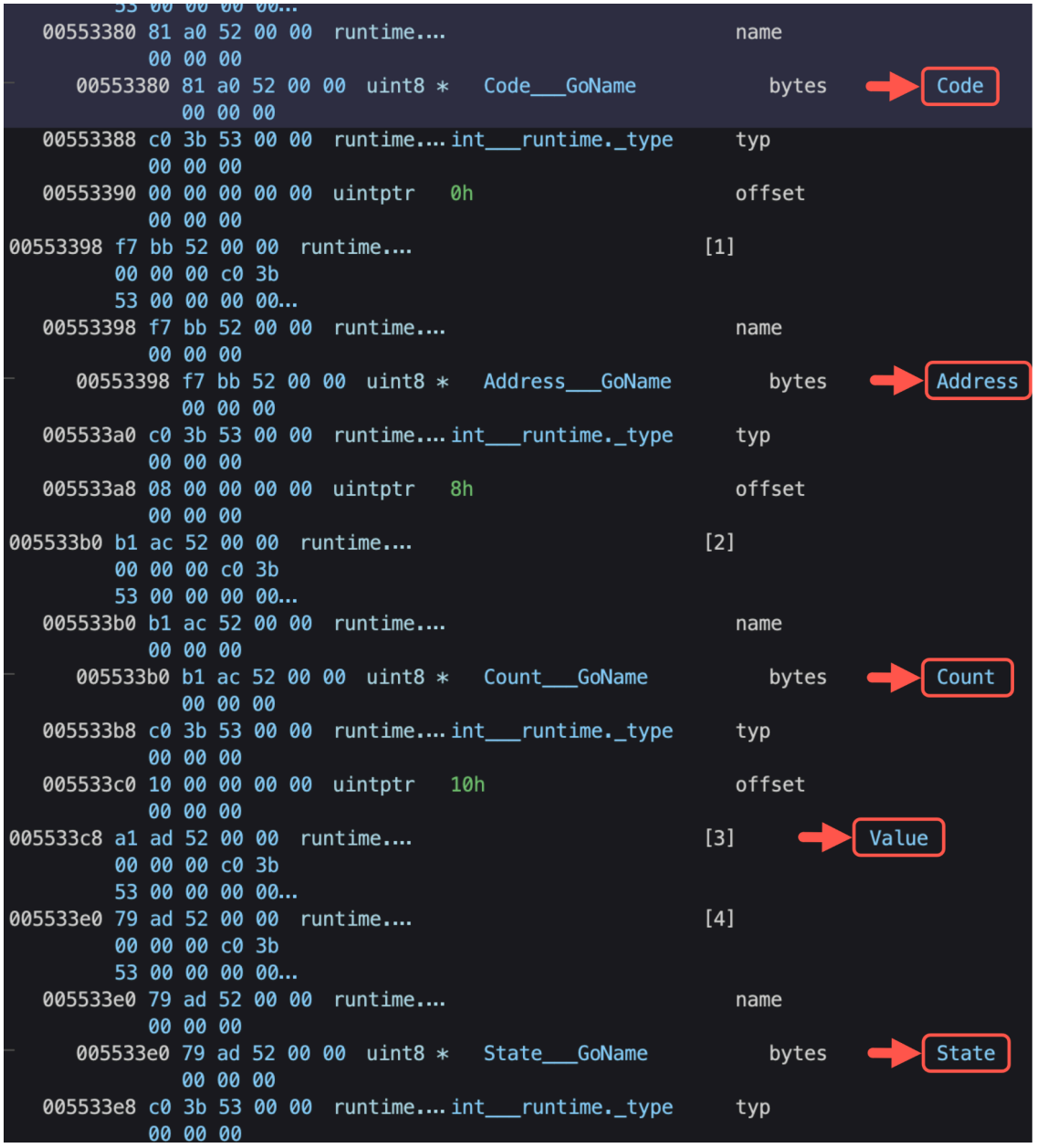


Figure 2. Binary Ninja showing FrostyGoop operations for Code, Address, Count, Value and State under the main::main.TaskList___runtime.structtype_fields register.

Figure 3 shows the timing configuration for main.Cycle.getCycleConfig.

```
layout.len = 8;
layout.str = (uint8 *)"15:04:05";
tVar22 = time::time.Parse(layout,local_90->StartTime);
tVar14 = time::time.ParseDuration(local_90->WorkTime);
tVar15 = time::time.ParseDuration(local_90->PeriodTime);
tVar16 = time::time.ParseDuration(local_90->IntervalTime);
```

Figure 3. Binary Ninja showing FrostyGoop timing configuration in the registry entry under main.Cycle.getCycleConfig(main.Cycle x,main.Cmd cmd).

FrostyGoop also leverages Goccy's go-json library, a faster JSON encoder and decoder compatible with the Go programming language standard encoding/json package. In addition, it incorporates a specific open-source execution controller named queues. The relative obscurity of this code means it can serve as another possible indicator of FrostyGoop.

Figure 4 shows our analysis of a Windows executable file for FrostyGoop within the tool Binary Ninja. This analysis reveals URLs from open-source libraries for modbus, go-json and queues.

```
2506  0x0019ab28 0x0059b528 23   24   .rdata  ascii   github.com/rolfl/modbus
2537  0x0019ae2f 0x0059b82f 24   25   .rdata  ascii   github.com/goccy/go-json
2565  0x0019b107 0x0059bb07 25   26   .rdata  ascii   github.com/hsblhsn/queues
```

Figure 4. Open-source libraries: Modbus, go-json and queues.

Although not all FrostyGoop samples contain the strings shown in Figure 4, other strings contained within those libraries can serve as part of the detection for this malware.

FrostyGoop also implements a debugger evasion technique by checking the BeingDebugged value in Windows' Process Environment Block (PEB). Figure 5 shows this method in the disassembled code from a FrostyGoop sample. This method provides an alternative way to check the PEB's BeingDebugged flag without calling IsDebuggerPresent(). Attackers use this technique to detect and avoid debuggers used by malware analysts.

```
void sub_7ffc3ef12410(int32_t arg1 @ rax) __noreturn

00007ffc3ef12410  void sub_7ffc3ef12410(int32_t arg1 @ rax) __noreturn

00007ffc3ef12410  4053              push    rbx {var_8}
00007ffc3ef12412  4881ec90050000    sub     rsp, 0x590
00007ffc3ef12419  488364242800      and     qword [rsp+0x28 {var_570}], 0x0
00007ffc3ef1241f  bb01000000        mov     ebx, 0x1
00007ffc3ef12424  8364243800        and     dword [rsp+0x38 {var_560}], 0x0
00007ffc3ef12429  895c2424          mov     dword [rsp+0x24 {var_574}], ebx  {0x1}
00007ffc3ef1242d  894c2420          mov     dword [rsp+0x20 {var_578}], ecx

00007ffc3ef12431  448ac3            mov     r8b, bl
00007ffc3ef12434  488d9424c0000000  lea     rdx, [rsp+0xc0 {var_4d8}]
00007ffc3ef1243c  488d4c2420        lea     rcx, [rsp+0x20]
00007ffc3ef12441  e82af3f9ff        call    sub_7ffc3eeb1770
00007ffc3ef12446  65488b0c25600000… mov     rcx, qword [gs:0x60]
00007ffc3ef1244f  80790200          cmp     byte [rcx+0x2 {_PEB::BeingDebugged}], 0x0
00007ffc3ef12453  7505              jne     0x7ffc3ef1245a

00007ffc3ef12455  80c3ff            add     bl, 0xff
00007ffc3ef12458  74d7              je      0x7ffc3ef12431

00007ffc3ef1245a  8bc8              mov     ecx, eax
00007ffc3ef1245c  e8afffffff        call    sub_7ffc3ef12410
```

Figure 5. Disassembled code from a FrostyGoop sample showing a check for the PEB's BeingDebugged flag.

Go-encrypt.exe Sample Analysis

Our investigation revealed a Windows executable sample named go-encrypt.exe written in Go that was not FrostyGoop, but it originally appeared on the same approximate date that other indicators of FrostyGoop were reported. Command-line options for this software reveal the file is used to encrypt and decrypt JSON files as illustrated in Figure 6.

```
C:\Users\Asher\Downloads>go-encrypt.exe -h
Usage of go-encrypt.exe:
  -decrypt
        true/false
  -encrypt
        true/false
  -input string
        input=[FILE.json]
  -output string
        output=[FILE.bin] (default "result.bin")

C:\Users\Asher\Downloads>
```

Figure 6. Command-line options for go-encrypt.exe.

After executing go-encrypt.exe using the -encrypt argument, it creates two files:

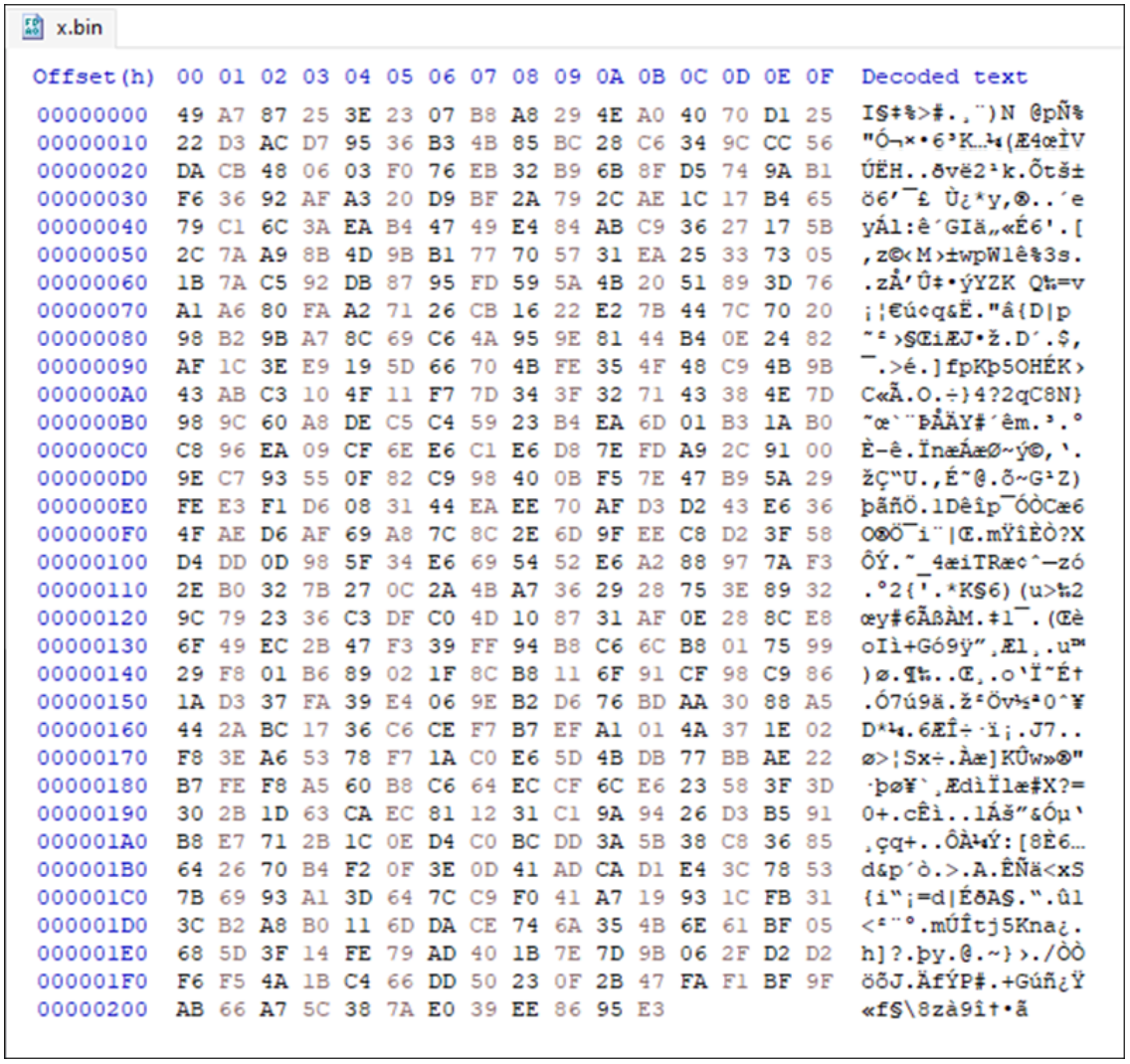
- An encrypted JSON
- A 32-byte file containing a decryption key named key

Figure 7 shows the encryption, decryption and the generated key.

```
C:\Users\Asher\Downloads>go-encrypt.exe -input task_test.json -output x.bin -encrypt true
2024/10/08 01:31:39 [runtime.main:proc.go:250][INFO] Key: %x
 [71 76 90 67 120 104 86 98 85 97 88 54 88 50 75 77 71 78 116 89 74 66 51 50 75 103 70 117
56 100 117 88]

C:\Users\Asher\Downloads>go-encrypt.exe -input x.bin -output clean.json -decrypt true
2024/10/08 01:31:54 [runtime.main:proc.go:250][INFO] Key: %x
 [71 76 90 67 120 104 86 98 85 97 88 54 88 50 75 77 71 78 116 89 74 66 51 50 75 103 70 117
56 100 117 88]
Decrypted file was created with file permissions 0777

C:\Users\Asher\Downloads>dir
 Volume in drive C has no label.
 Volume Serial Number is 0934-ECDE

 Directory of C:\Users\Asher\Downloads

10/08/2024  01:31 AM    <DIR>          .
10/08/2024  01:07 AM    <DIR>          ..
10/08/2024  01:31 AM               379 clean.json
10/08/2024  12:57 AM         1,773,568 go-encrypt.exe
10/08/2024  01:31 AM                32 key
10/08/2024  12:58 AM               379 task_test.json
10/08/2024  01:31 AM               524 x.bin
               5 File(s)      1,774,882 bytes
```

Figure 7. Using go-encrypt.exe to encrypt and decrypt a JSON file.

Figure 8 shows the content of an encrypted JSON file generated by go-encrypt.exe.



x.bin

Offset(h)	00	01	02	03	04	05	06	07	08	09	0A	0B	0C	0D	0E	0F	Decoded text
00000000	49	A7	87	25	3E	23	07	B8	A8	29	4E	A0	40	70	D1	25	I§‡%>#.¸¨)N @pÑ%
00000010	22	D3	AC	D7	95	36	B3	4B	85	BC	28	C6	34	9C	CC	56	"Ó¬×•6³K…¼(Æ4œÌV
00000020	DA	CB	48	06	03	F0	76	EB	32	B9	6B	8F	D5	74	9A	B1	ÚËH..ðvë2¹k.Õtš±
00000030	F6	36	92	AF	A3	20	D9	BF	2A	79	2C	AE	1C	17	B4	65	ö6'¯£ Ù¿*y,®..´e
00000040	79	C1	6C	3A	EA	B4	47	49	E4	84	AB	C9	36	27	17	5B	yÁl:ê´GIä„«É6'.[
00000050	2C	7A	A9	8B	4D	9B	B1	77	70	57	31	EA	25	33	73	05	,z©‹M›±wpW1ê%3s.
00000060	1B	7A	C5	92	DB	87	95	FD	59	5A	4B	20	51	89	3D	76	.zÅ'Û‡•ýYZK Q‰=v
00000070	A1	A6	80	FA	A2	71	26	CB	16	22	E2	7B	44	7C	70	20	¡¦€úcq&Ë."â{D|p
00000080	98	B2	9B	A7	8C	69	C6	4A	95	9E	81	44	B4	0E	24	82	˜²›§ŒiÆJ•ž.D´.$,
00000090	AF	1C	3E	E9	19	5D	66	70	4B	FE	35	4F	48	C9	4B	9B	¯.>é.]fpKþ5OHÉK›
000000A0	43	AB	C3	10	4F	11	F7	7D	34	3F	32	71	43	38	4E	7D	C«Ã.O.÷}4?2qC8N}
000000B0	98	9C	60	A8	DE	C5	C4	59	23	B4	EA	6D	01	B3	1A	B0	˜œ`¨ÞÅÄY#´êm.³.°
000000C0	C8	96	EA	09	CF	6E	E6	C1	E6	D8	7E	FD	A9	2C	91	00	È–ê.ÏnæÁæØ~ý©,'.
000000D0	9E	C7	93	55	0F	82	C9	98	40	0B	F5	7E	47	B9	5A	29	žÇ"U.‚É˜@.õ~G¹Z)
000000E0	FE	E3	F1	D6	08	31	44	EA	EE	70	AF	D3	D2	43	E6	36	þãñÖ.1DêîpÓÒCæ6
000000F0	4F	AE	D6	AF	69	A8	7C	8C	2E	6D	9F	EE	C8	D2	3F	58	O®Ö¯i¨|Œ.mŸîÈÒ?X
00000100	D4	DD	0D	98	5F	34	E6	69	54	52	E6	A2	88	97	7A	F3	ÔÝ.˜_4æiTRæ¢ˆ—zó
00000110	2E	B0	32	7B	27	0C	2A	4B	A7	36	29	28	75	3E	89	32	.°2{'.*K§6)(u>‰2
00000120	9C	79	23	36	C3	DF	C0	4D	10	87	31	AF	0E	28	8C	E8	œy#6ÃßÀM.‡1¯.(Œè
00000130	6F	49	EC	2B	47	F3	39	FF	94	B8	C6	6C	B8	01	75	99	oIì+Gó9ÿ"¸Æl¸.u™
00000140	29	F8	01	B6	89	02	1F	8C	B8	11	6F	91	CF	98	C9	86	)ø.¶‰..Œ¸.o'Ï˜É†
00000150	1A	D3	37	FA	39	E4	06	9E	B2	D6	76	BD	AA	30	88	A5	.Ó7ú9ä.ž²Öv½ª0ˆ¥
00000160	44	2A	BC	17	36	C6	CE	F7	B7	EF	A1	01	4A	37	1E	02	D*¼.6ÆÎ÷·ï¡.J7..
00000170	F8	3E	A6	53	78	F7	1A	C0	E6	5D	4B	DB	77	BB	AE	22	ø>¦Sx÷.Àæ]KÛw»®"
00000180	B7	FE	F8	A5	60	B8	C6	64	EC	CF	6C	E6	23	58	3F	3D	·þø¥`¸ÆdìÏlæ#X?=
00000190	30	2B	1D	63	CA	EC	81	12	31	C1	9A	94	26	D3	B5	91	0+.cÊì..1Áš"&Óµ'
000001A0	B8	E7	71	2B	1C	0E	D4	C0	BC	DD	3A	5B	38	C8	36	85	¸çq+..ÔÀ¼Ý:[8È6…
000001B0	64	26	70	B4	F2	0F	3E	0D	41	AD	CA	D1	E4	3C	78	53	d&p´ò.>.A.ÊÑä<xS
000001C0	7B	69	93	A1	3D	64	7C	C9	F0	41	A7	19	93	1C	FB	31	{i"¡=d|ÉðA§.".û1
000001D0	3C	B2	A8	B0	11	6D	DA	CE	74	6A	35	4B	6E	61	BF	05	<²¨°.mÚÎtj5Kna¿.
000001E0	68	5D	3F	14	FE	79	AD	40	1B	7E	7D	9B	06	2F	D2	D2	h]?.þy.@.~}›./ÒÒ
000001F0	F6	F5	4A	1B	C4	66	DD	50	23	0F	2B	47	FA	F1	BF	9F	öõJ.ÄfÝP#.+Gúñ¿Ÿ
00000200	AB	66	A7	5C	38	7A	E0	39	EE	86	95	E3					«f§\8zà9î†•ã

Figure 8. An encrypted JSON file viewed in a hex editor.

Figure 9 shows a filtered list of processes generated by go-encrypt.exe in Process Monitor. We have highlighted when go-encrypt.exe created the decryption file named key and the 32 character content of this key file.

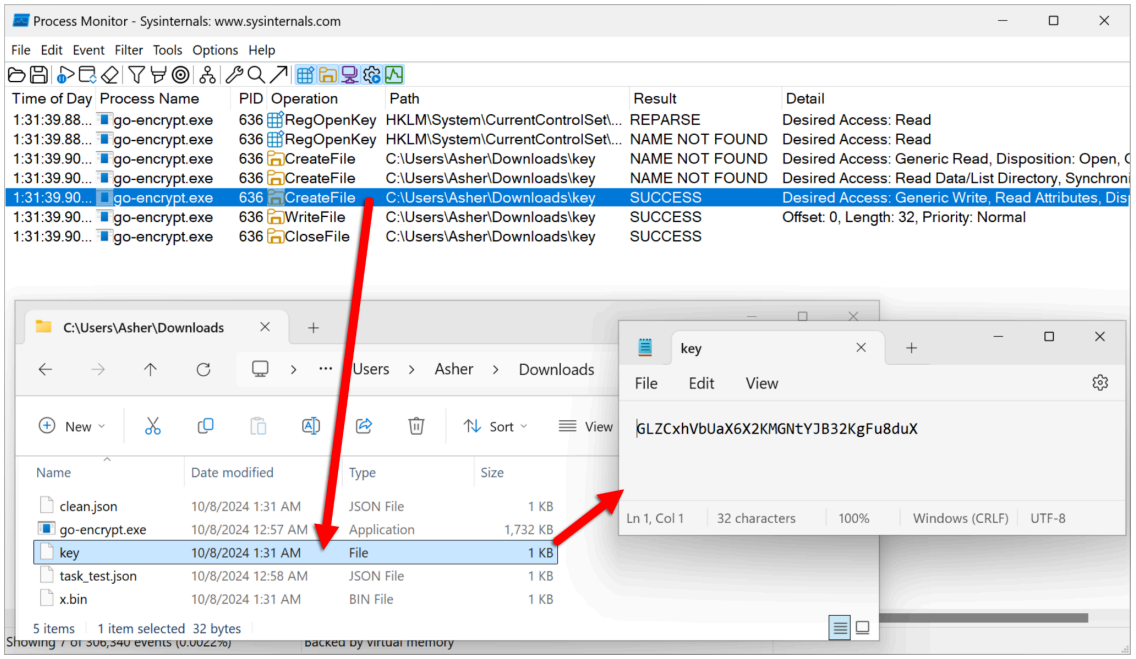


Figure 9. Process Monitor showing go-encrypt.exe generating the key file.

Decompiling go-encrypt.exe revealed it uses the Cipher Feedback (CFB) mode of the AES encryption algorithm to create the encryption/decryption key in the key file as shown in Figures 10 and 11.

```
                    main::main.encrypt                              XREF[4]:     ma
                                                                                 00
                                                                                 00
004c53c0 49 3b 66 10     CMP        RSP,qword ptr [R14 + 0x10]=>CURRENT_G.stackgua..
004c53c4 0f 86 8b        JBE        LAB_004c5555
         01 00 00
004c53ca 48 83 ec 78     SUB        RSP,0x78
004c53ce 48 89 6c        MOV        qword ptr [RSP + local_8],RBP
         24 70
004c53d3 48 8d 6c        LEA        RBP=>local_8,[RSP + 0x70]
         24 70
004c53d8 48 89 84        MOV        qword ptr [RSP + param_10],param_1
         24 80 00
         00 00
004c53e0 4c 89 84        MOV        qword ptr [RSP + param_15],param_6
         24 a8 00
         00 00
004c53e8 48 89 b4        MOV        qword ptr [RSP + param_14],param_5
         24 a0 00
         00 00
004c53f0 48 89 bc        MOV        qword ptr [RSP + param_13],param_4
         24 98 00
         00 00
004c53f8 e8 43 ae        CALL       crypto/aes::crypto/aes.NewCipher
         fb ff
004c53fd 0f 1f 00        NOP        dword ptr [param_1]
004c5400 48 85 c9        TEST       param_3,param_3
004c5403 74 0b           JZ         LAB_004c5410
004c5405 0f 85 3a        JNZ        LAB_004c5545
         01 00 00
004c540b e9 39 01        JMP        LAB_004c5549
         00 00
```

Figure 10. Decompiled code of go-encrypt.exe showing its AES main encryption routine.

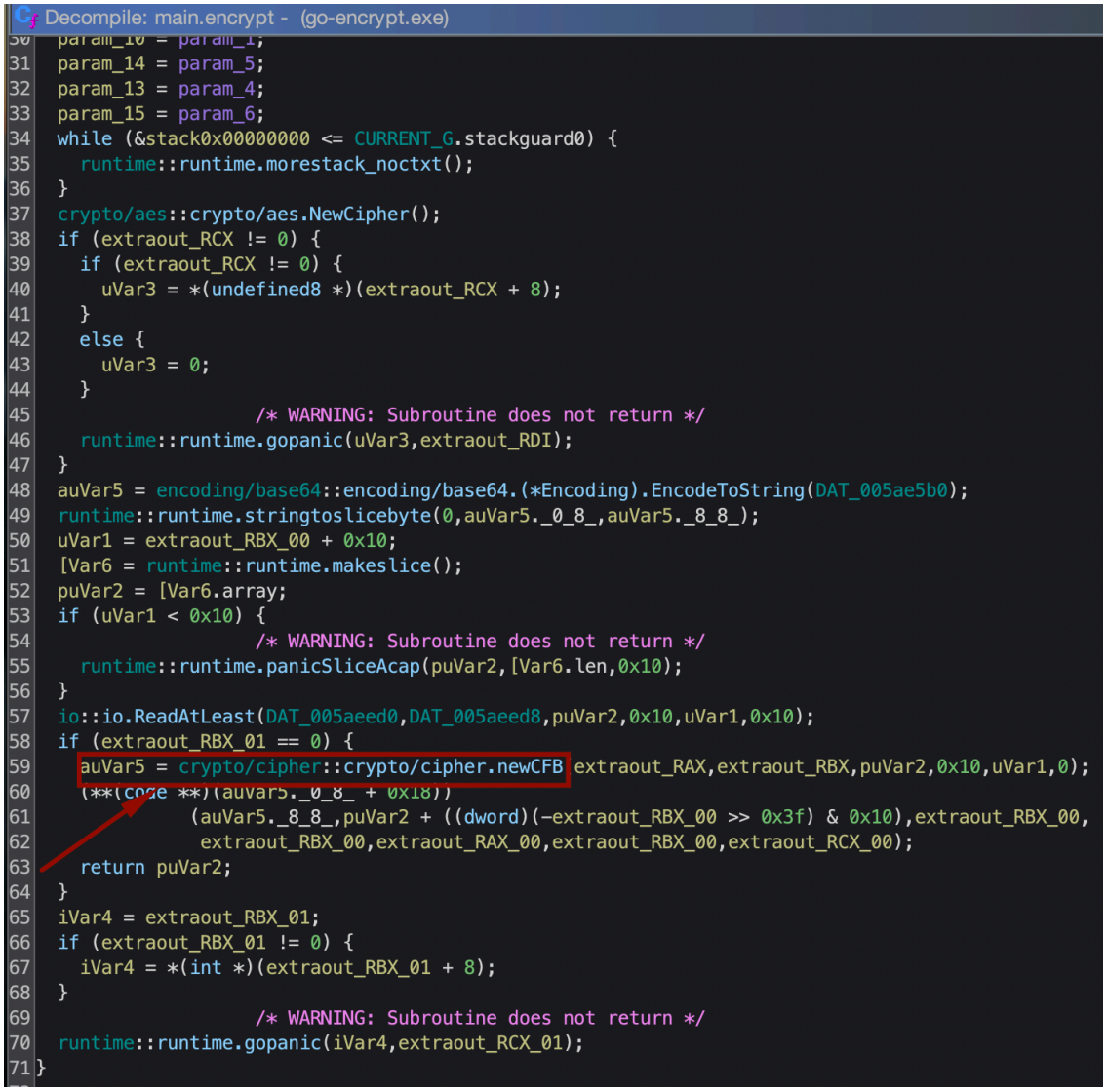


Figure 11. Decompiled code of go-encrypt.exe showing CFB mode.

As shown previously for the key generated in Figure 7, the key value is in decimal format. The decimal value of the key from Figure 7 is:

- 71 76 90 67 120 104 86 98 85 97 88 54 88 50 75 77 71 78 116 89 74 66 51 50 75 103 70 117 56 100 117 88

We can decode these decimal numbers into the 32-byte value of the key through a variety of methods, like the Python script shown in Figure 12. This script will convert the binary values to hexadecimal.

Figure 12. Example of a Python script to convert the decimal value of the key to hexadecimal.

The 32-byte value of the key in hexadecimal is:

- 47 4c 5a 43 78 68 56 62 55 61 58 36 58 32 4b 4d 47 4e 74 59 4a 42 33 32 4b 67 46 75 38 64 75 58

According to Go's documentation for aes.NewCipher, a byte stream of 32 bytes corresponds to a 256-bit AES encryption in CFBmode. We confirmed the 32-byte hexadecimal value of the key from our example matches the ASCII value in the key file using CyberChef as shown below in Figure 13.

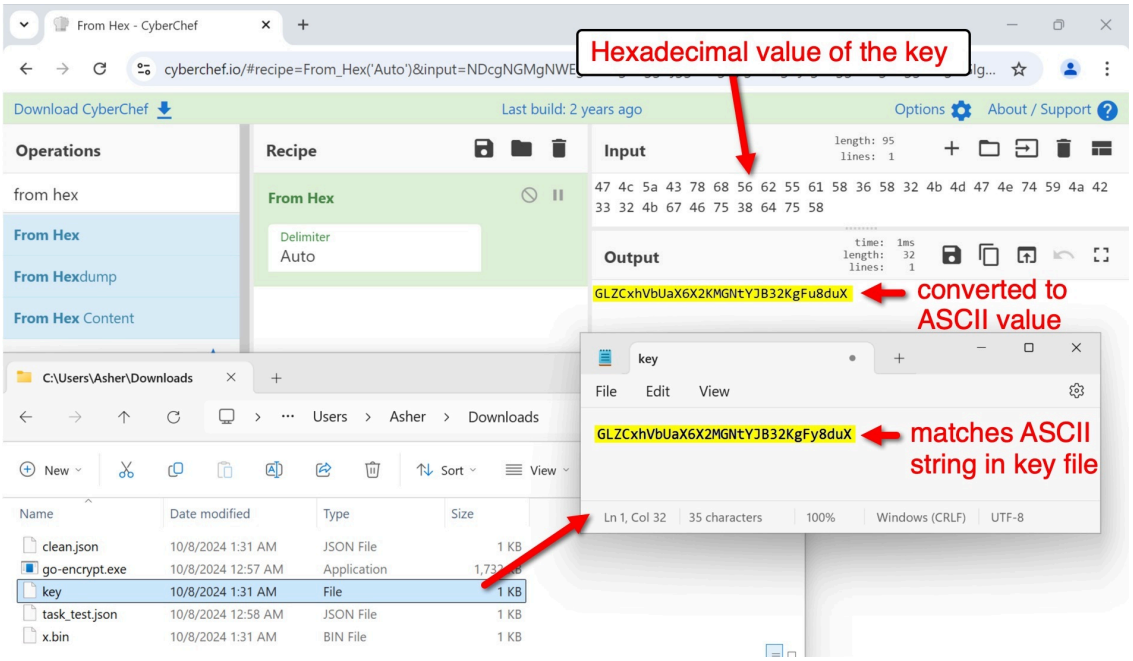


Figure 13. Using CyberChef to verify the hex value matches the ASCII value of the key file.

Although we cannot confirm go-encrypt.exe was used for the FrostyGoop attack, two circumstances indicate the attackers might have used it during this activity:

- First, it is used to encrypt and decrypt JSON files, and encrypted JSON files are an essential element of FrostyGoop functionality.
- Second, go-encrypt.exe first appeared in the wild around the same time as the FrostyGoop samples and the task_test.json file.

Therefore, attackers could have used this piece of software to conceal target information in JSON files for later use to perpetrate attacks.

Investigation of the Targeted Infrastructure

According to the Dragos report on FrostyGoop, they initially discovered this malware in April 2024. This report notes an example of a FrostyGoop configuration file named task_test.json.

Searching VirusTotal, we found one occurrence of task_test.json on Oct. 10, 2023. Pivoting on that file, we discovered Windows executable files that we subsequently identified as FrostyGoop and go-encrypt.exe.

Figure 14 shows the same first-seen date of Oct. 10, 2023, for task_test.json, go-encrypt.exe and the other Windows executable files.

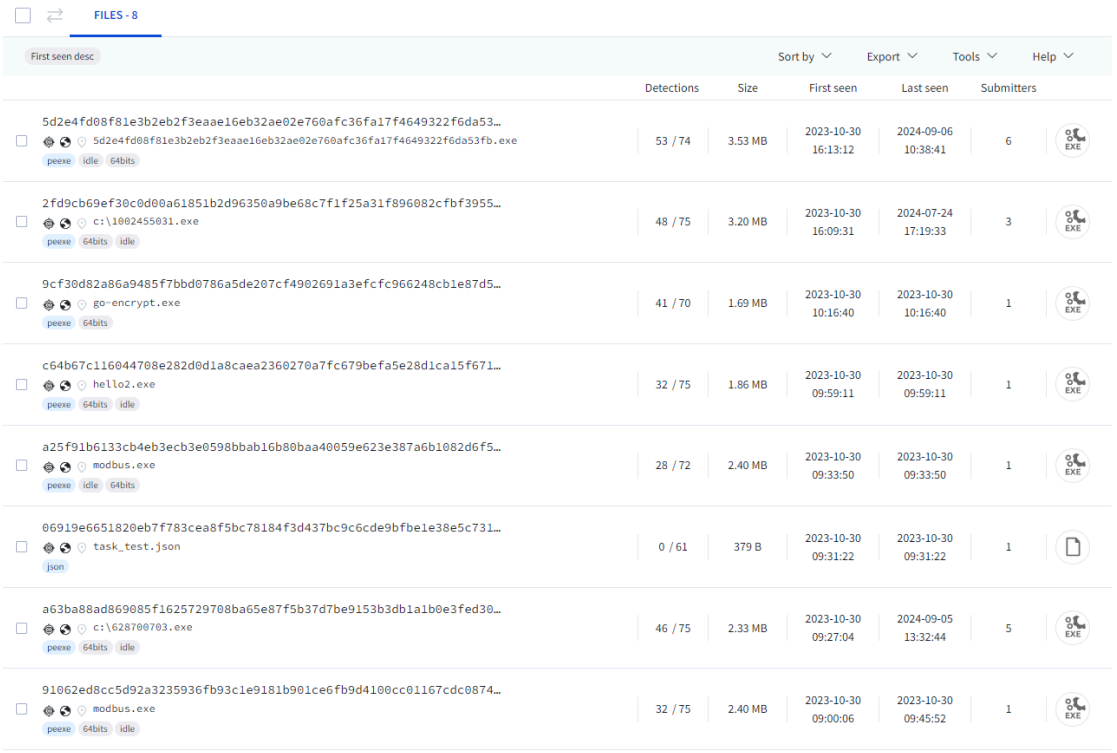
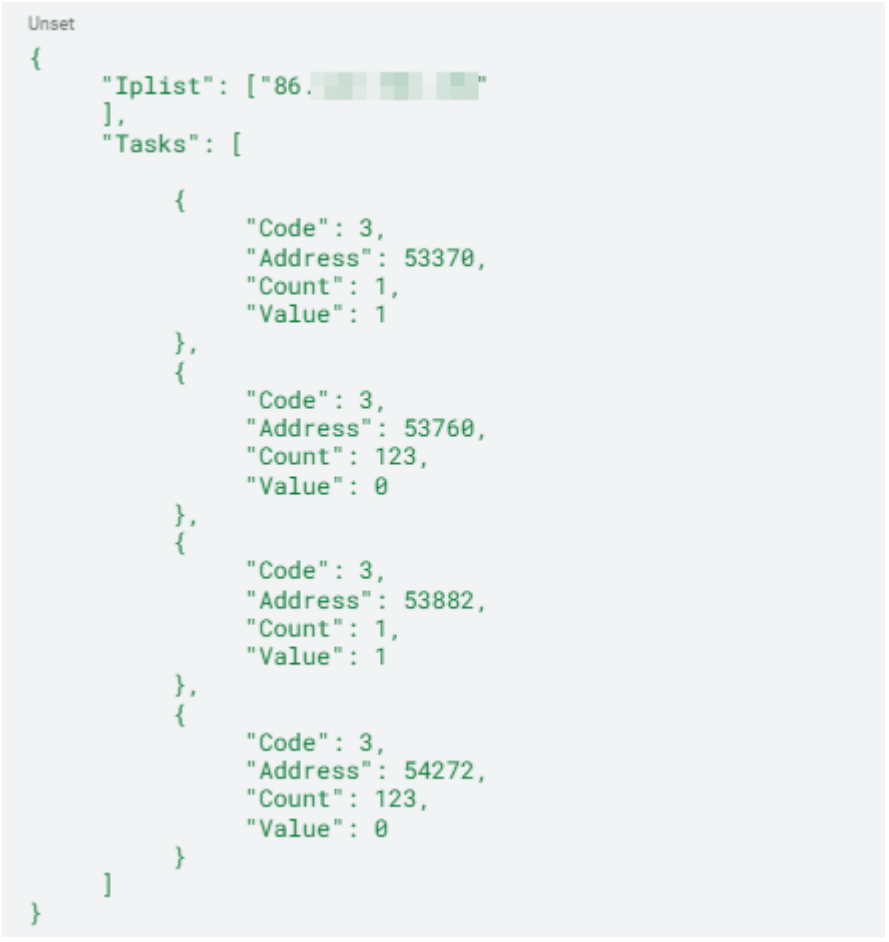


Figure 14. Malware samples and task_test.json detection timestamps in VirusTotal.

The data structure of task_test.json and its key/values are the format we would expect to be used as a configuration file by a FrostyGoop executable file. Our analysis of FrostyGoop samples indicates the malware performs read, write and write-multiple Modbus operations. The content of the task_test.json sample depicted in Figure 15 only shows read operations (Code 3).



```
Unset
{
     "Iplist": ["86.[redacted]"
     ],
     "Tasks": [

          {
               "Code": 3,
               "Address": 53370,
               "Count": 1,
               "Value": 1
          },
          {
               "Code": 3,
               "Address": 53760,
               "Count": 123,
               "Value": 0
          },
          {
               "Code": 3,
               "Address": 53882,
               "Count": 1,
               "Value": 1
          },
          {
               "Code": 3,
               "Address": 54272,
               "Count": 123,
               "Value": 0
          }
     ]
}
```

Figure 15. The content of task_test.json used by a FrostyGoop malware sample.

The IP address contained in this JSON file corresponds to an ENCO control device located in Romania as noted.

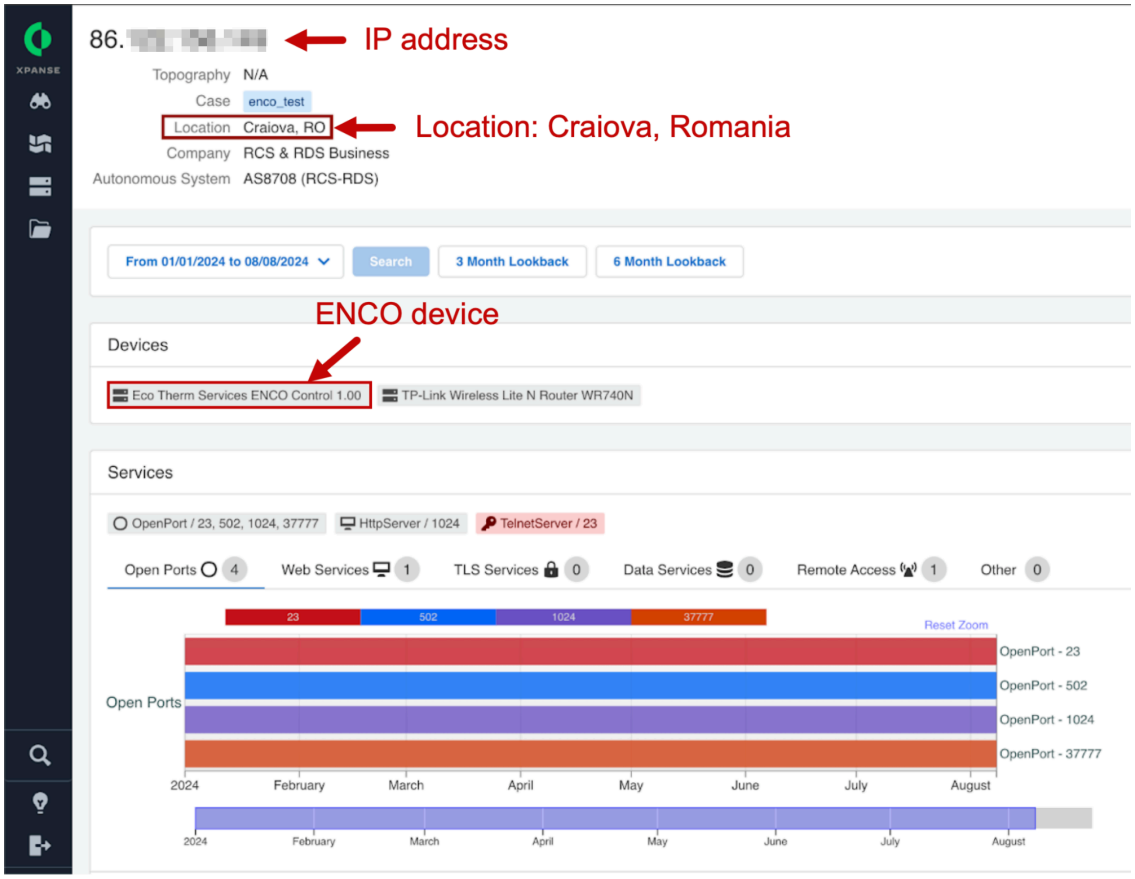


Figure 16. Xpanse query indicating it is an ENCO device in Romania.

Widening our search for exposed ENCO devices, our telemetry revealed 32 IP addresses, all located in either Romania or Ukraine as noted in Figure 17.

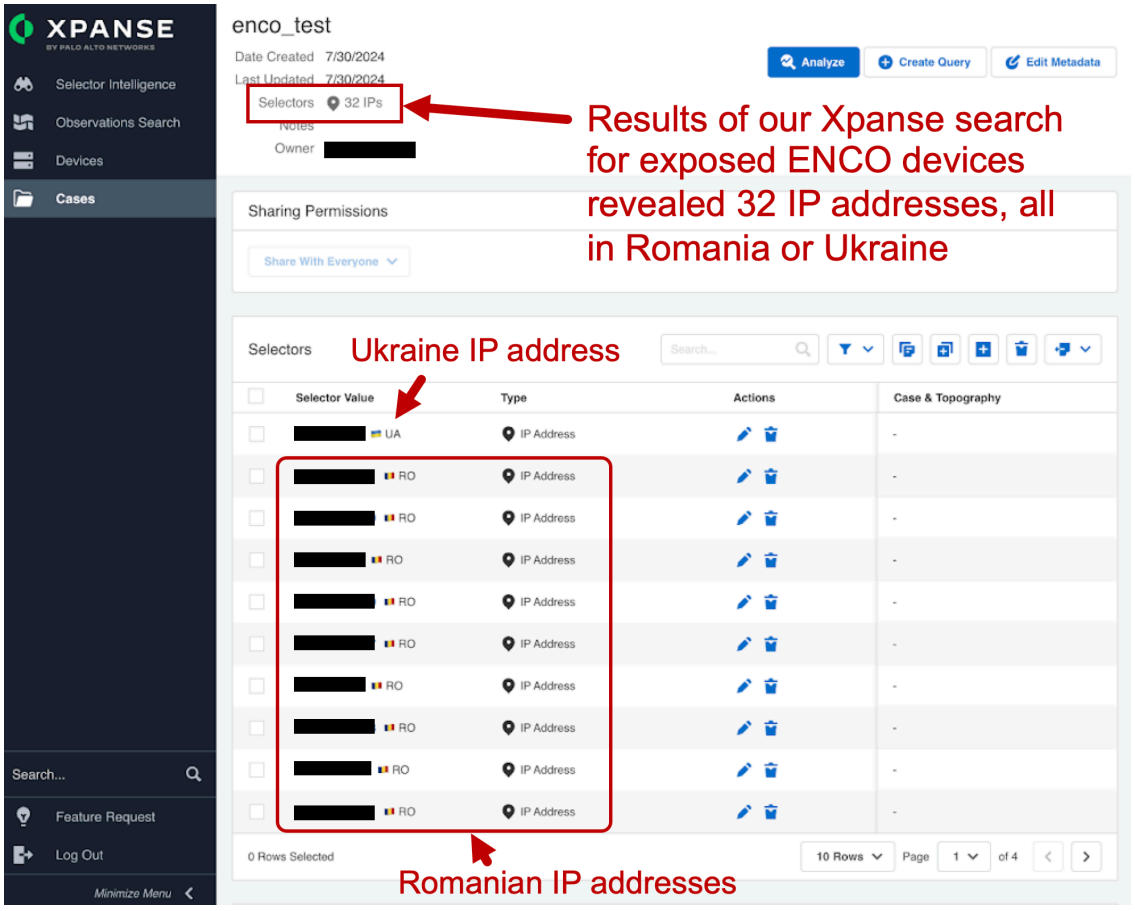


Figure 17. Xpanse query of IP addresses with exposed ENCO devices.

The ENCO devices we discovered all have TCP port 23 exposed for Telnet. Telnet provides a communications and management interface that is considered obsolete because it has no built-in encryption.

Simply connecting to an exposed ENCO device over Telnet reveals an ENCO banner with a list of available commands as shown below in Figure 18. This provides a reportedly easy method to probe for and identify ENCO programmable logic controller (PLC) devices on the internet.

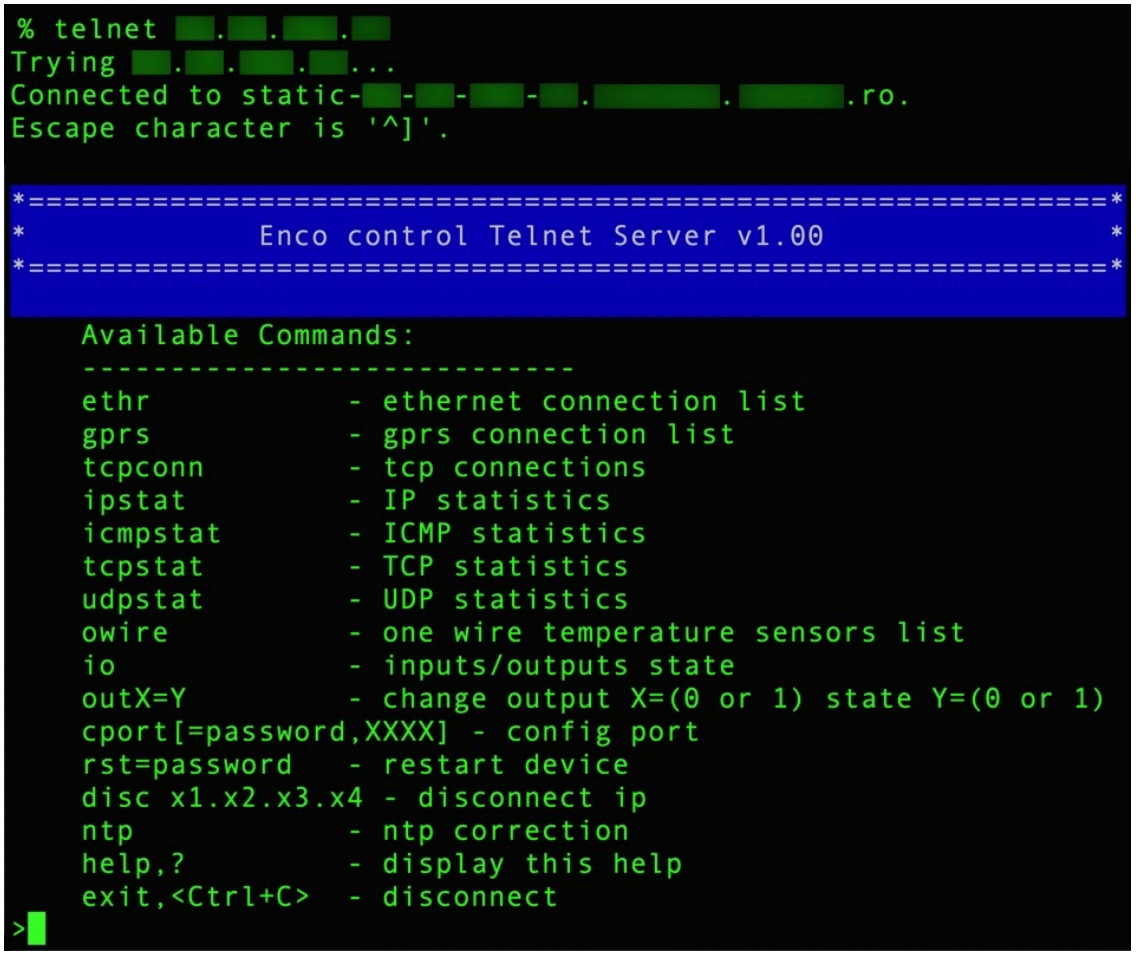
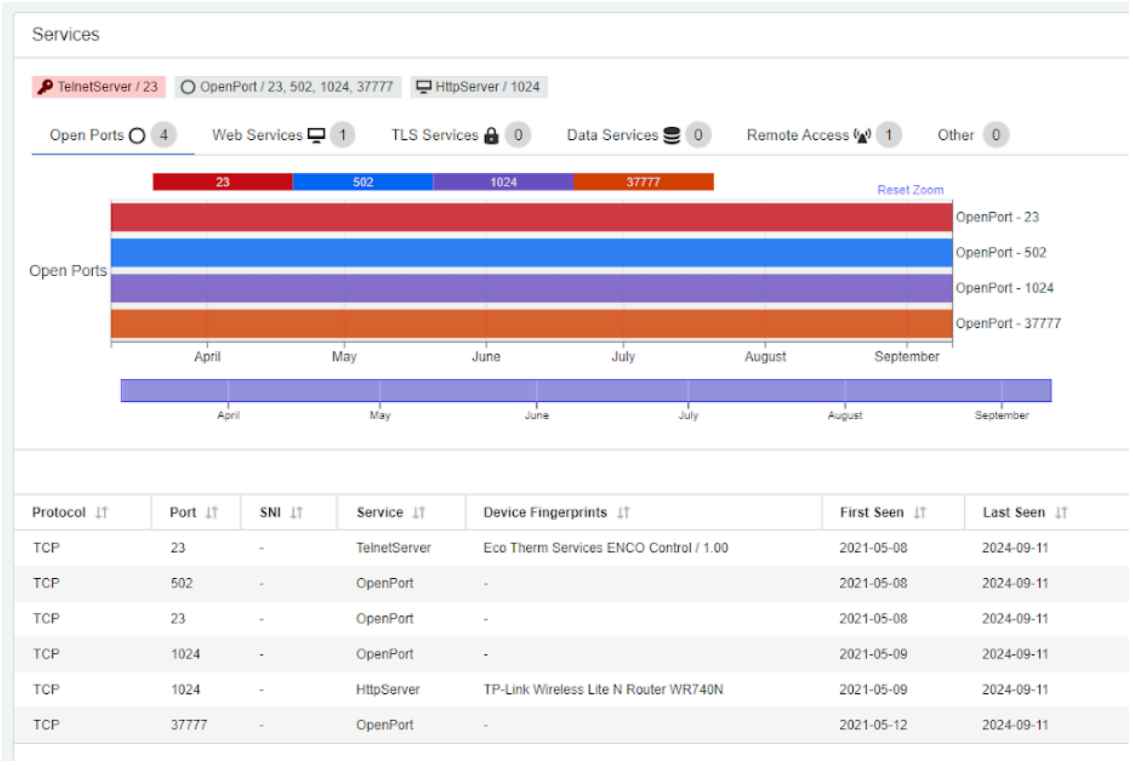


Figure 18. Telnet banner from an exposed ENCO device.

Figure 19 shows a portion of our Xpanse report covering details of the network services running on the server listed in task_test.json. This matches the exposed ports among the other ENCO exposed devices we discovered:

- TCP ports 23 (Telnet)
- 502 (Modbus)
- 1024 (Router WebUI)
- 37777 (ENCO connect port)



Protocol	Port	SNI	Service	Device Fingerprints	First Seen	Last Seen
TCP	23	-	TelnetServer	Eco Therm Services ENCO Control / 1.00	2021-05-08	2024-09-11
TCP	502	-	OpenPort	-	2021-05-08	2024-09-11
TCP	23	-	OpenPort	-	2021-05-08	2024-09-11
TCP	1024	-	OpenPort	-	2021-05-09	2024-09-11
TCP	1024	-	HttpServer	TP-Link Wireless Lite N Router WR740N	2021-05-09	2024-09-11
TCP	37777	-	OpenPort	-	2021-05-12	2024-09-11

Figure 19. Xpanse report for open ports on.

We can glean further information on the ENCO device by accessing it using a web browser and recording the traffic. Figure 20 shows a login screen shown when accessing the ENCO device from a web browser. By viewing the web traffic in Wireshark and examining the HTTP response headers, we find the router is being used as a web server and the name of the router is TP-LINK Wireless Lite N Router WR740N.

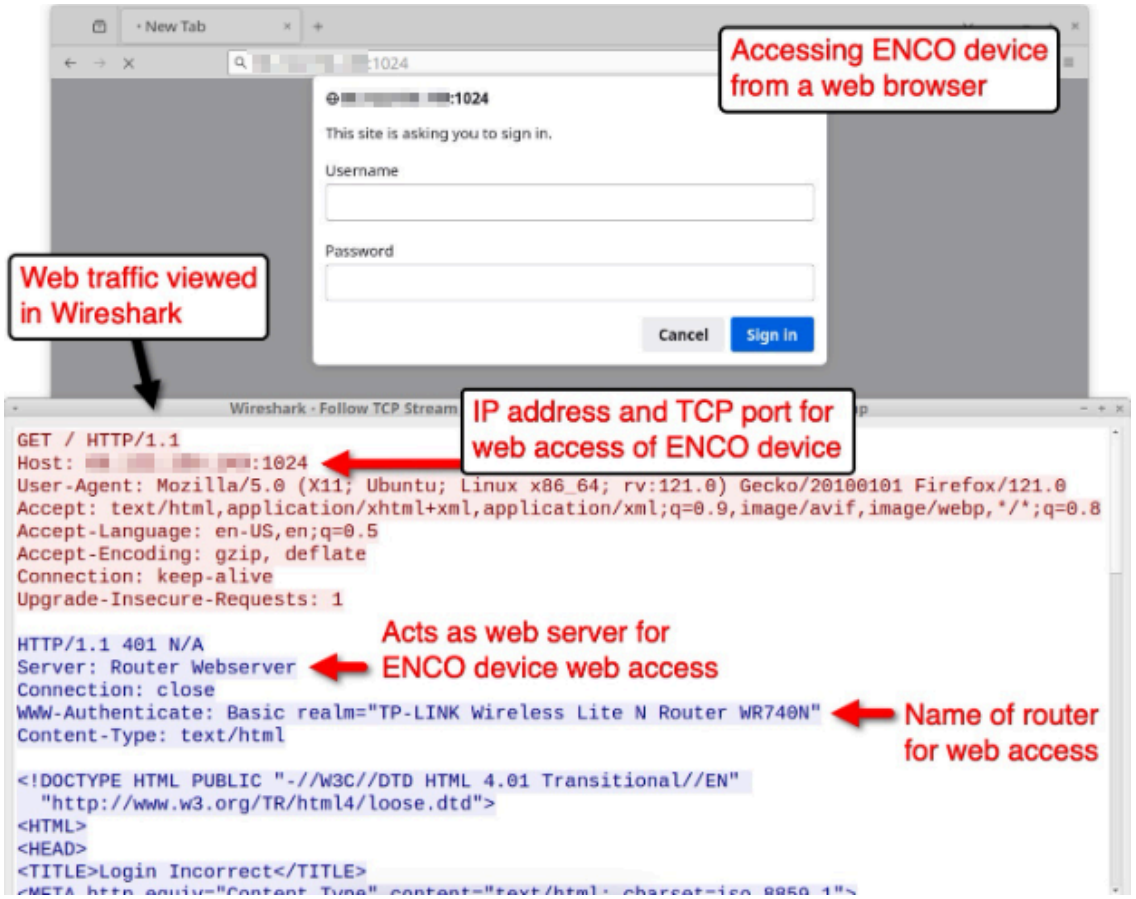


Figure 20. Information gleaned from accessing an ENCO device over a web browser.

According to the NIST website, versions 1 and 2 of the WR740N router's firmware are susceptible to a command injection vulnerability. However, there is no hard evidence to indicate that the attackers exploited this vulnerability in the July 2024 FrostyGoop attack.

Network Traffic Analysis

To analyze FrostyGoop traffic, we tested two samples using task_test.json as the configuration file. The two FrostyGoop samples have the following SHA256 hashes:

- 5d2e4fd08f81e3b2eb2f3eaae16eb32ae02e760afc36fa17f4649322f6da53fb
- a63ba88ad869085f1625729708ba65e87f5b37d7be9153b3db1a1b0e3fed309c

The task_test.json configuration file only has a function code value of 3, which represents a Modbus command to read the holding registers. Accordingly, the FrostyGoop samples only generated commands to read the holding registers of the targeted device at over TCP port 502.

Figure 21 shows an example of the Modbus traffic generated during our test of the FrostyGoop samples, filtered in Wireshark with a customized column display. It reveals Modbus traffic to over TCP port 502, as well as the four register values specified in the task_test.json configuration file:

- 53370
- 53882

- 53760
- 54272

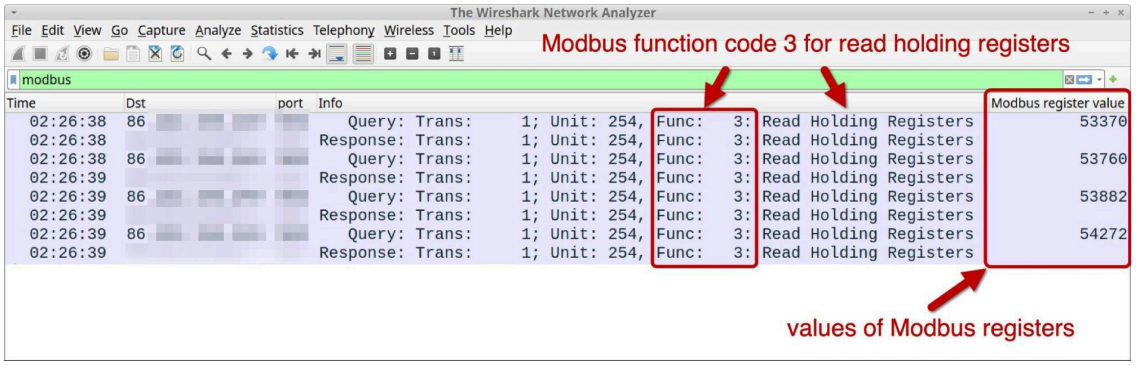


Figure 21. Example of Modbus traffic from our FrostyGoop sample test filtered in Wireshark.

Figure 22 shows an example of a Modbus function code 3 request to read values from the holding registers of the ENCO device, starting with the register number 53760 for the next 123 registries. The device responded with values from registry 53760-53882. These registry entries hold UINT16 values for unsigned integers that can range from 0-65535.

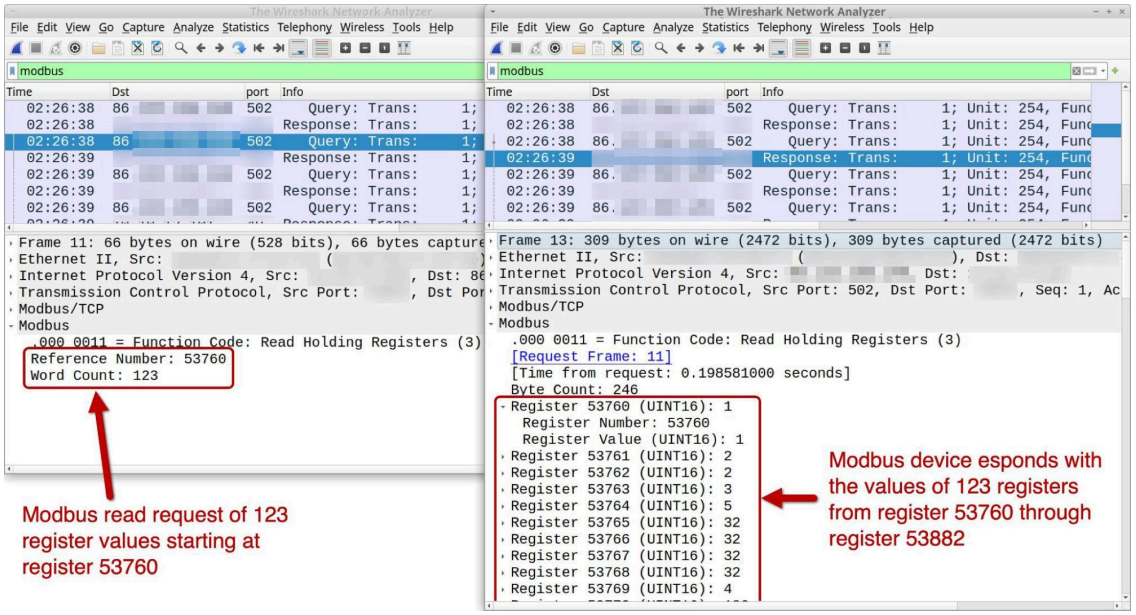


Figure 22. Modbus interaction with the hardware device.

We reverse engineered the samples to track down their functions. Our analysis revealed that the taskWorker function selects actions performed through the following function parameters:

- read holding registers (3)
- write (6)
- writeMultiple (6)

If the JSON configuration file contains the number 1 as a word count value, only one register is returned. If it does not contain the number 1 as a word count value, more than one register is returned.

Figure 23 shows a code snippet from a FrostyGoop sample with the logic to select Modbus operations depending on the value provided:

- 3 for read holding registers
- 6 for write single holding register
- 16 for write multiple holding registers operation

```
int64_t main.Task.taskWorker(int64_t arg1, int64_t arg2, int64_t arg3, int64_t arg4, int64_t arg5 @ rax,
0051f806    if (arg5 == 3)
0051f806    {
0051f8ca        rdi = arg1;
0051f8e7        uint64_t rax_8;
0051f8e7        uint64_t rcx_6;
0051f8e7        rax_8 = main.MbConfig.read(arg_30, arg3, arg4, arg8, rdi, arg9);
0051f8ec        rdx_1 = rcx_6;
0051f8ef        rsi_1 = rax_8;
0051f8f2        r8 = 0x1a;
0051f8fa        rcx = var_e0;
0051f902        arg6 = var_140;
0051f806    }
0051f806    else if (arg5 == 6)
0051f810    {
0051f880        rdi = arg7;
0051f8a0        uint64_t rax_5;
0051f8a0        uint64_t rcx_4;
0051f8a0        rax_5 = main.MbConfig.write(arg_30, arg3, arg4, arg8, rdi, arg9);
0051f8a5        rdx_1 = rcx_4;
0051f8a8        rsi_1 = rax_5;
0051f8ab        r8 = 0x16;
0051f8b3        rcx = var_e0;
0051f8bb        arg6 = var_140;
0051f810    }
0051f810    else if (arg5 == 0x10)
0051f816    {
0051f82e        rdi = arg1;
0051f853        uint64_t rax_2;
0051f853        uint64_t rcx_2;
0051f853        rax_2 = main.MbConfig.writeMultiple(arg_30, arg5, arg8, arg3, arg4, rdi, arg9, zmm15);
0051f858        rdx_1 = rcx_2;
0051f85b        rsi_1 = rax_2;
0051f85e        r8 = 0x21;
0051f866        rcx = var_e0;
0051f86e        arg6 = var_140;
0051f816    }
0051f816    else
0051f816    {
0051f818        rdx_1 = 0;
0051f81a        rdi = 0;
0051f81c        rsi_1 = 0;
0051f81e        r8 = 0;
0051f816    }
0051f816
```

Figure 23. Code snippet from a FrostyGoop sample showing how it implements Modbus operations.

Conclusion

With cyberattacks against ICS/OT devices and critical infrastructure increasing in recent years, the cybersecurity landscape in these types of environments has become increasingly dangerous. Countries like Ukraine, Romania, Israel, China, Russia and the United States have all been affected by attacks targeting their critical infrastructure. Prior to these incidents, cybersecurity in OT was not considered an essential part of their defensive operations.

The past decade has seen an increase in CS-centric malware, with FrostyGoop being the most recent prominent example. During this time frame, the number of OT and internet of things (IoT) devices exposed to the internet has drastically increased.

An increasing number of OT networks have been connected with IT networks to facilitate facilities management. This has unleashed new ways to perform cyberattacks that can not only damage the cyberspace realm, but also the physical world. Malicious actors can send control commands to field devices easily disguised as regular operations within network traffic, making the activity more difficult to detect and prevent.

For these reasons, we must implement security measures to prevent and mitigate these attacks. Palo Alto Networks customers are better protected from the threats discussed in this blog through the following products:

- Industrial OT Security is designed to:
    - Use machine learning techniques to detect abnormal network traffic and abnormal behavior in engineering workstations and field devices
    - Raise alerts in the event of a compromised environment, based on anomalous command access
    - Generate alerts based on Modbus operations
    - Implement analytics rules for detection of suspicious traffic including anonymous telnet login, brute-force login attempts, default credentials usage
    - Cover and identify Common Vulnerabilities and Exposures (CVEs) in MikroTik and other common routers
    - Leverage upstream Advanced WildFire and Advanced Threat Prevention detections, along with IoT device detection capabilities, to detect malware command and control communication
    - Detect devices running vulnerable versions of firmware
- Next-Generation Firewall (NGFW) and Advanced Threat Prevention are designed to:
    - Provide complete visibility and control of the applications in use across all users and devices in all locations all the time
    - Automatically reprogram your firewall with the latest intelligence using inline machine learning as well as the application and threat signatures
    - Implement rules TID 31667 (Modbus read coils) and TID 31668 (Modbus write coils), which allows administrators to identify abnormal devices performing Modbus operations
    - Implement MikroTik CVEs related to prevent remote code execution and command injection vulnerabilities from being exploited within the network
- Advanced WildFire is designed to:
    - Identify malicious binaries and make verdict determinations when analyzing executing processes
    - Implement detection rules to identify, block and prevent deployment of FrostyGoop/BUSTLEBERM and its variants, as well as other ICS-centric ransomware and malware
- Cortex Xpanse is designed to:
    - Provide a complete, accurate and continuously updated inventory of all global internet-facing assets, including exposed OT services and devices
    - Enable discovery, evaluation and mitigation of cyberattack surface risks
    - Facilitate evaluation of supplier risk
- Cortex XDR and XSIAM are designed to:
    - Accurately detect threats with behavioral analytics and reveal the root cause to speed up investigations
    - Better protect against malware discussed in this article through Cortex XDR, including WildFire, Behavioral Threat Protection and the Local Analysis module

- Unit 42 researchers at Palo Alto Networks are committed to discovering new malware and threats. We share our findings and feed the results back into our products and services, so our customers are better protected.

If you think you may have been compromised or have an urgent matter, get in touch with the Unit 42 Incident Response team or call:

- North America Toll-Free: 866.486.4842 (866.4.UNIT42)
- EMEA: +31.20.299.3130
- APAC: +65.6983.8730
- Japan: +81.50.1790.0200

Palo Alto Networks has shared these findings with our fellow Cyber Threat Alliance (CTA) members. CTA members use this intelligence to rapidly deploy protections to their customers and to systematically disrupt malicious cyber actors. Learn more about the Cyber Threat Alliance.
