Packet-Level Signatures for Smart Home Devices

Rahmadi Trimananda, Janus Varmarken,
Athina Markopoulou, and Brian Demsky

UCI University of California, Irvine

Home

Smart Home

Smart **Plugs**

Smart Home

Smart **Plugs**

Light Bulbs

UCI University of California, Irvine

Smart Home

Smart **Plugs**

Light Bulbs

Thermostats

Smart Home

Smart **Plugs**

Light Bulbs

Thermostats

Cameras

UCI University of California, Irvine

Smart Home

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Light Bulbs

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Doorbells

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Smart Home

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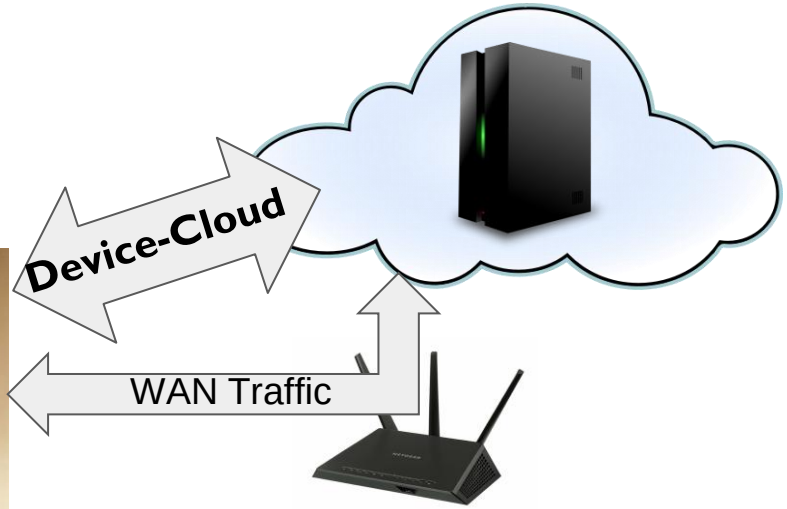
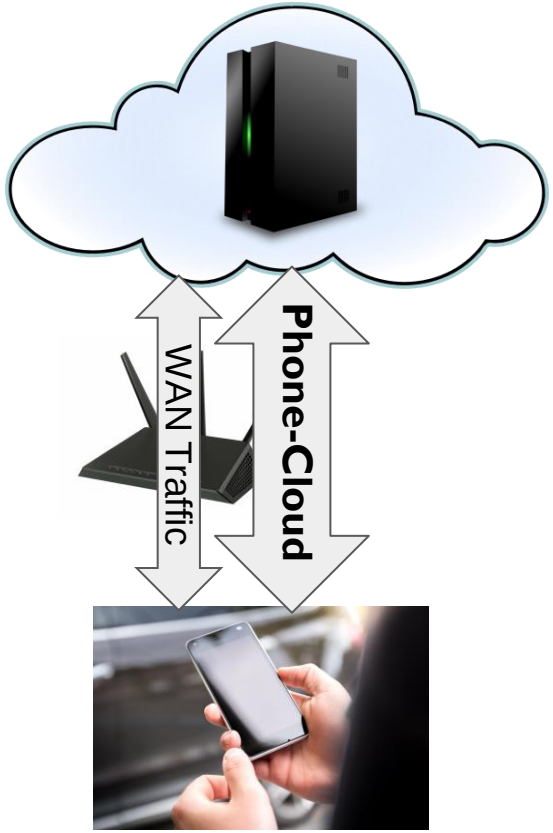


Smart Home



Smart Home

NOT-SO PRIVATE Smart Home

WAN Sniffer

WAN Sniffer

WAN Sniffer

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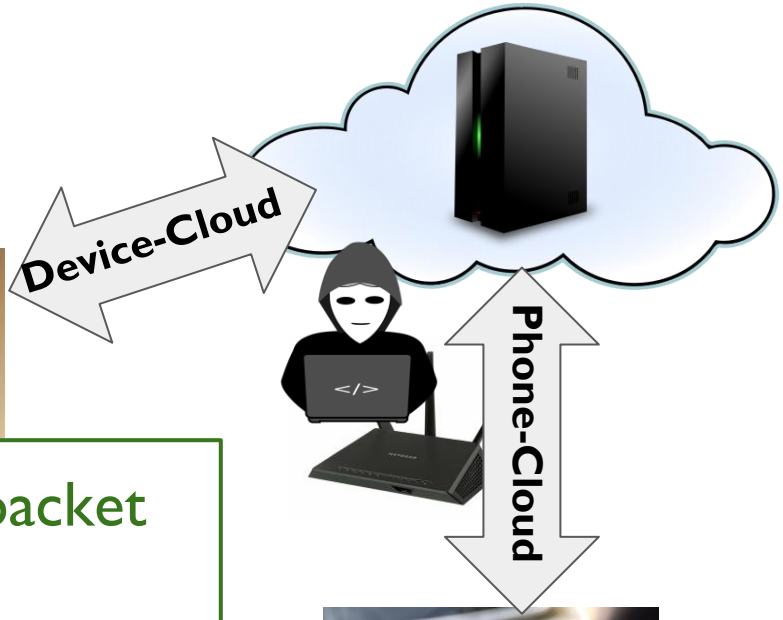
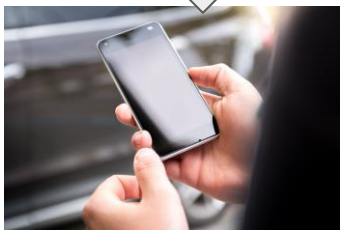


1) Can look into TCP/IP packet
2) Can see IP address
3) Cannot see MAC address



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Wi-Fi Sniffer

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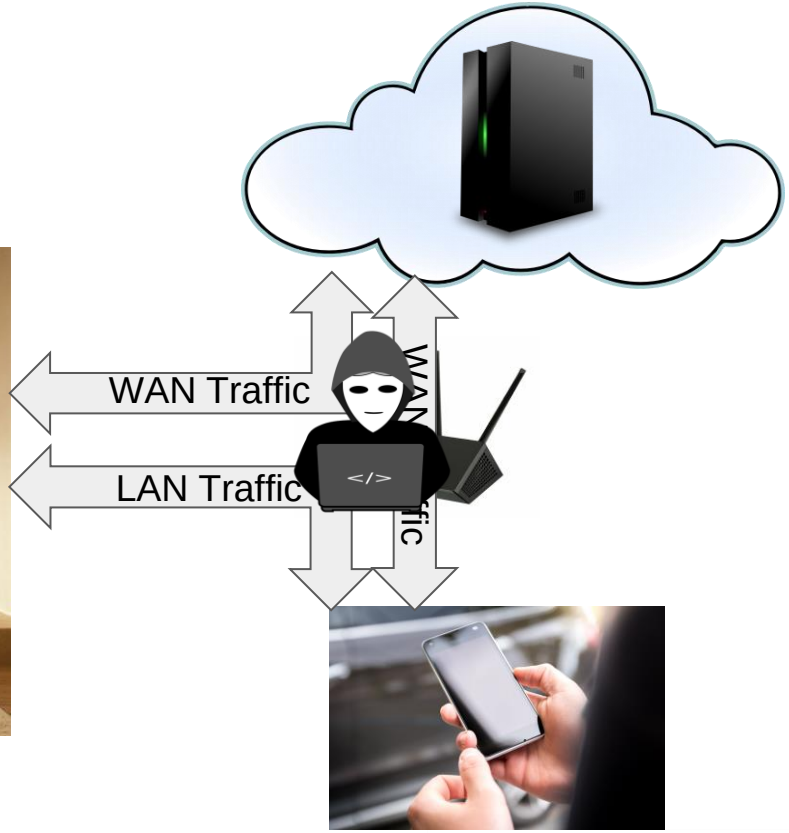

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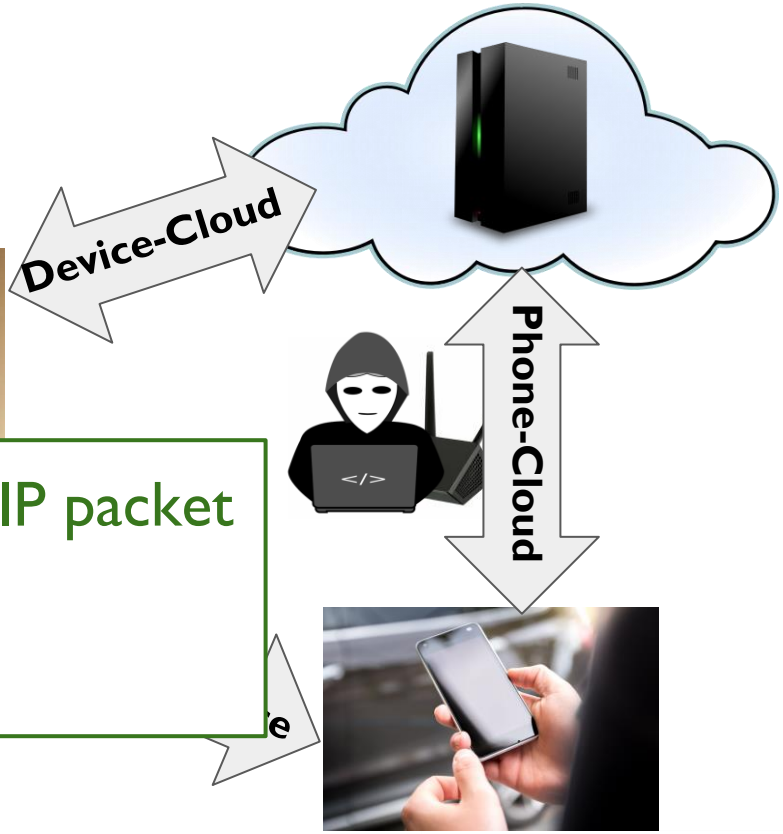

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State-of-the-Art

- Specific protocols (ZigBee/Z-Wave) Homonit [CCS'18]
- Volume-based Apthorpe et al. [PETS'19]
- ML-based approaches HomeSnitch [WiSec'19]
- IoT datasets Ren et al. [IMC'19], Alrawi et al. [S&P'19]

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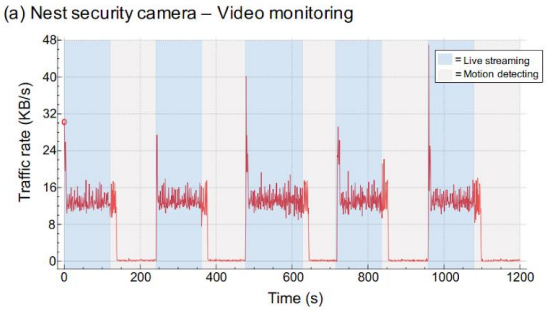

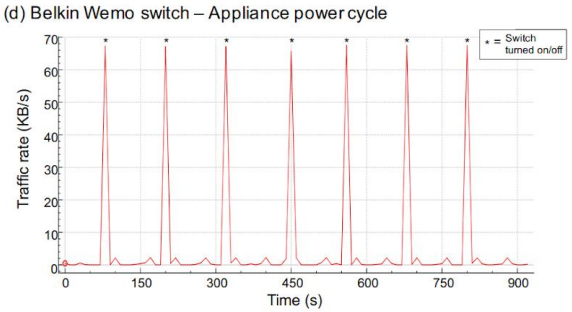

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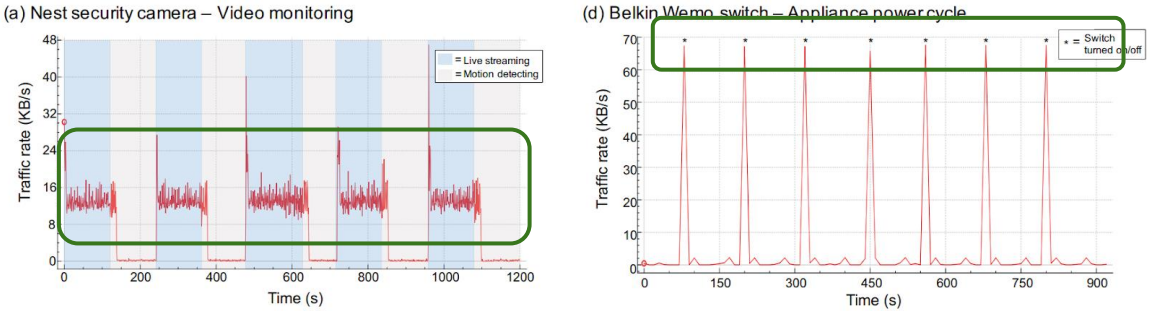

Volume spike is event

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Feature	Category	Importance
Avg. bytes from client per seq.	**Throughput**	**0.213104**
Avg. bytes from server per seq.	**Throughput**	**0.072519**
Aggregate server bytes sent for ADU	Throughput	0.105775
Aggregate client bytes sent fo ADU	Throughput	0.117552
Min bytes from client for single seq.	**Burstiness**	**0.038917**
Min bytes from server for single seq.	**Burstiness**	**0.038344**
Max bytes from server for single seq.	Burstiness	0.079063
Max bytes from client for single seq.	Burstiness	0.135909
Stdev of bytes for server seq.	Burstiness	0.054491
Stdev of bytes for client seq.	Burstiness	0.050798
Server sequences per ADU	Synchronicity	0.013566
Client sequences per ADU	Synchronicity	0.016211
Total time of connection	Duration	0.063750

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Network statistics as features

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- Device study
  - Network traffic characteristics
- Public datasets
  - Mon(IoT)r
    https://moniotrlab.ccis.neu.edu/imc19/
  - YourThings
    https://yourthings.info/

Outline

I. Background and Problem Statement

II. Key Observation: Packet-Level Signatures

III. The PingPong System

IV. Conclusion

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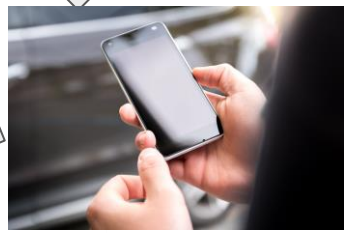
Smart Home

Local Phone

Toggle ON Plug

LAN Traffic

Phone-Device



Key Observation: Ping-Pong

Toggle ON Plug

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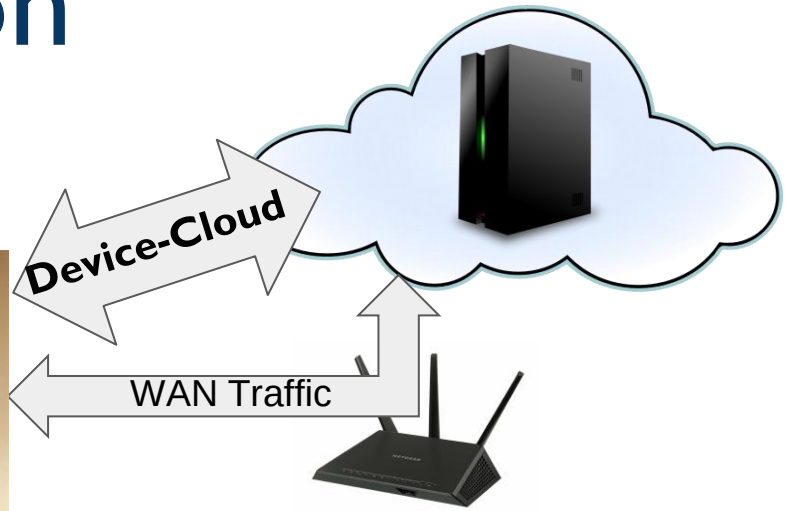
Toggle ON Plug

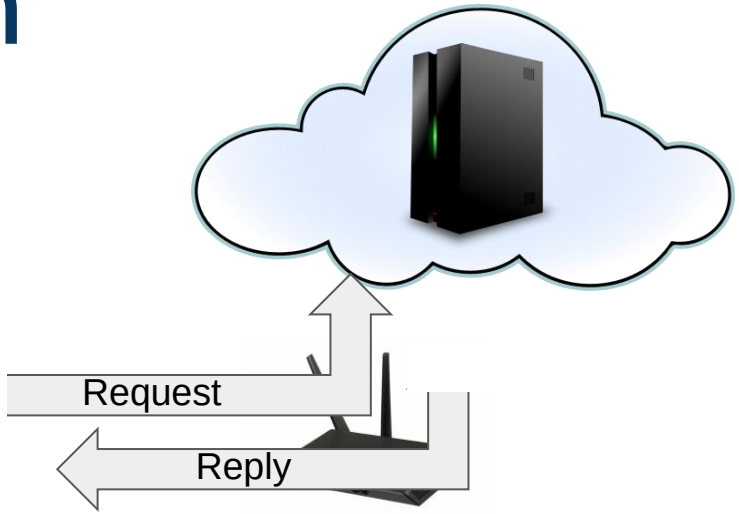
Key Observation

Toggle ON Plug



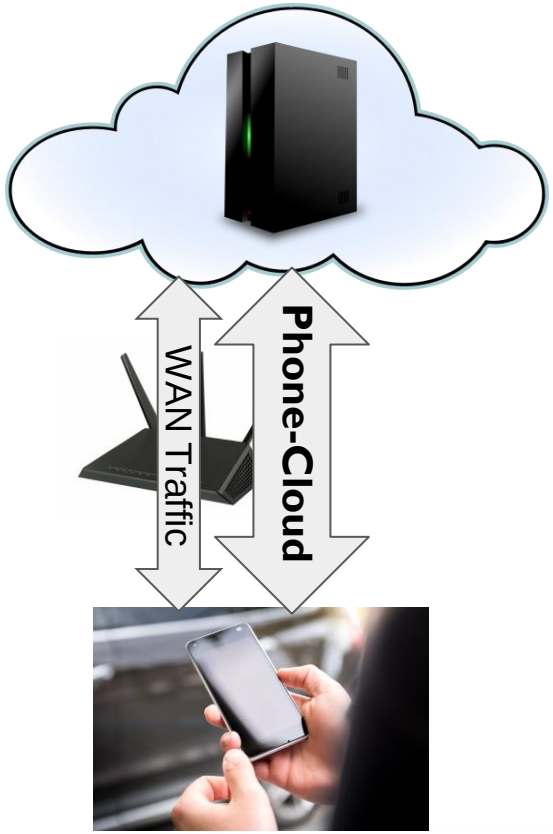
Key Observation

Toggle ON Plug



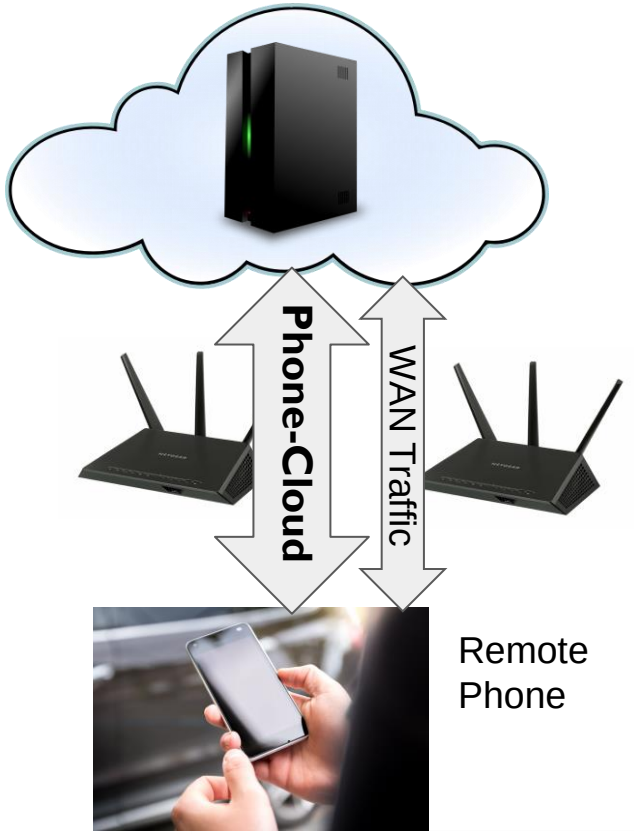
Remote Phone

Toggle ON Plug



Remote Phone

Toggle ON Plug



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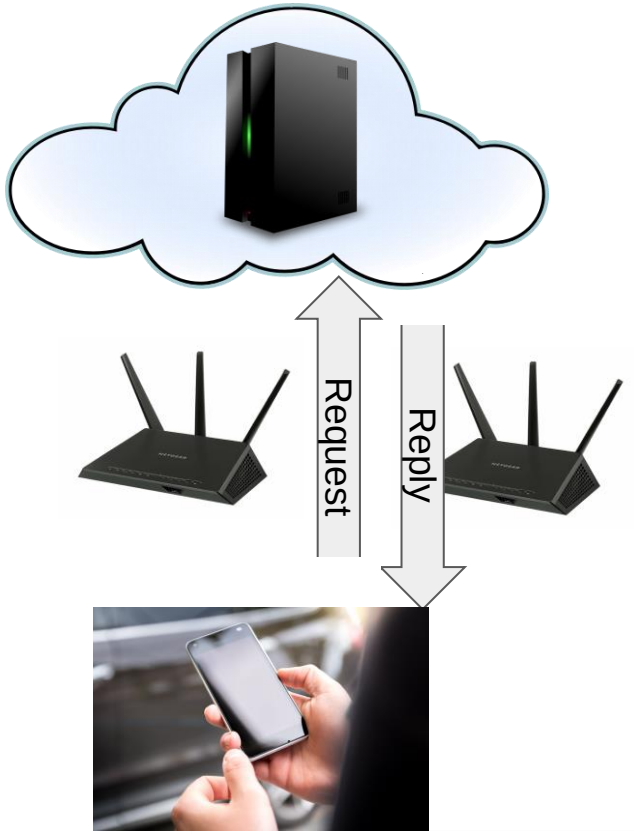

Remote Phone

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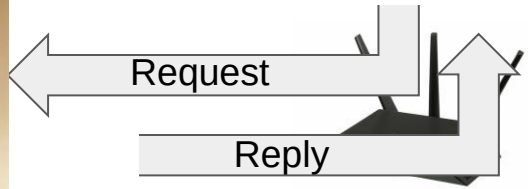

Home Automation

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Toggle ON Plug

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Home Automation

IFTTT

Toggle ON Plug

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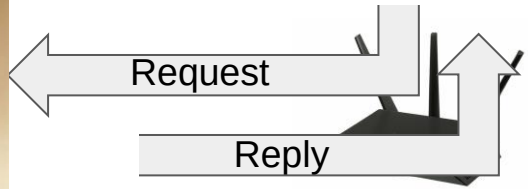

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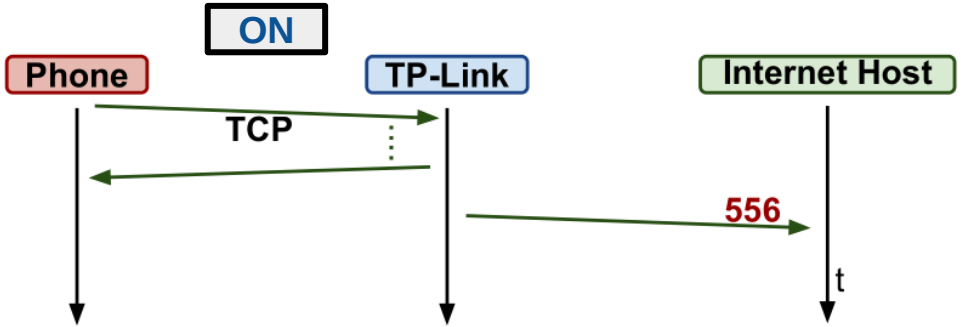
Ping-Pong in TP-Link Plug



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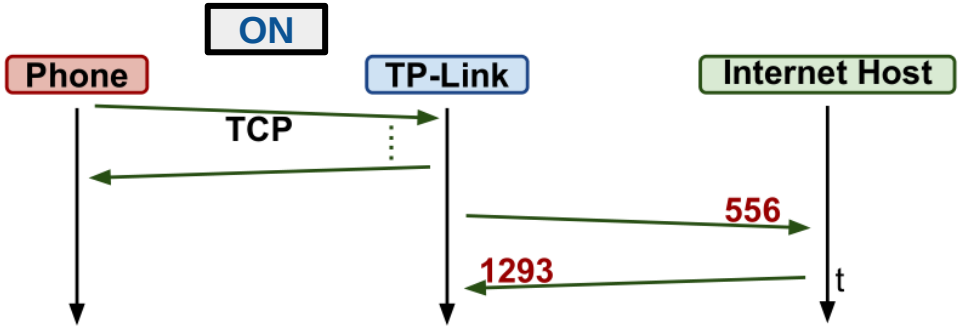

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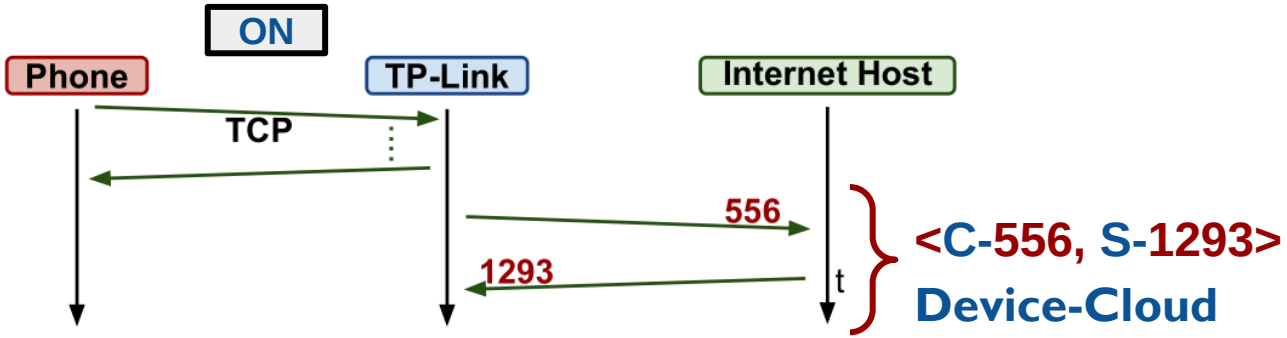

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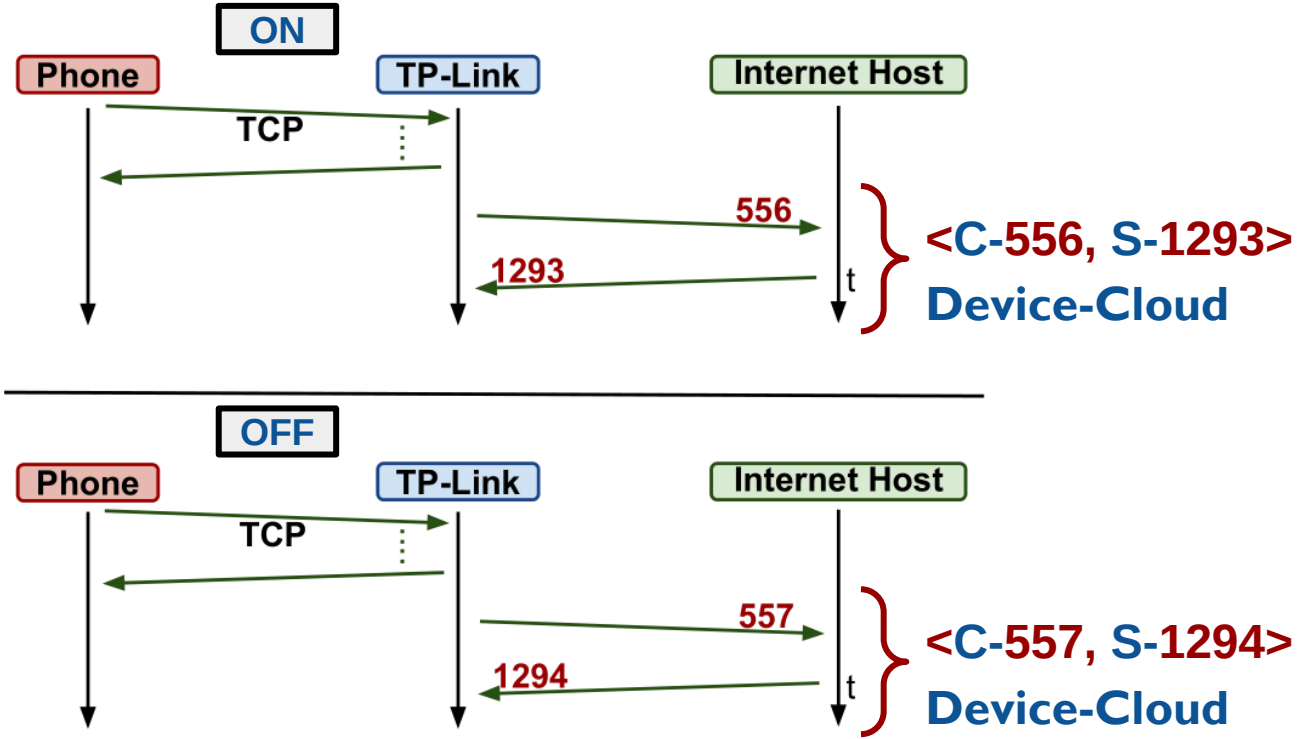
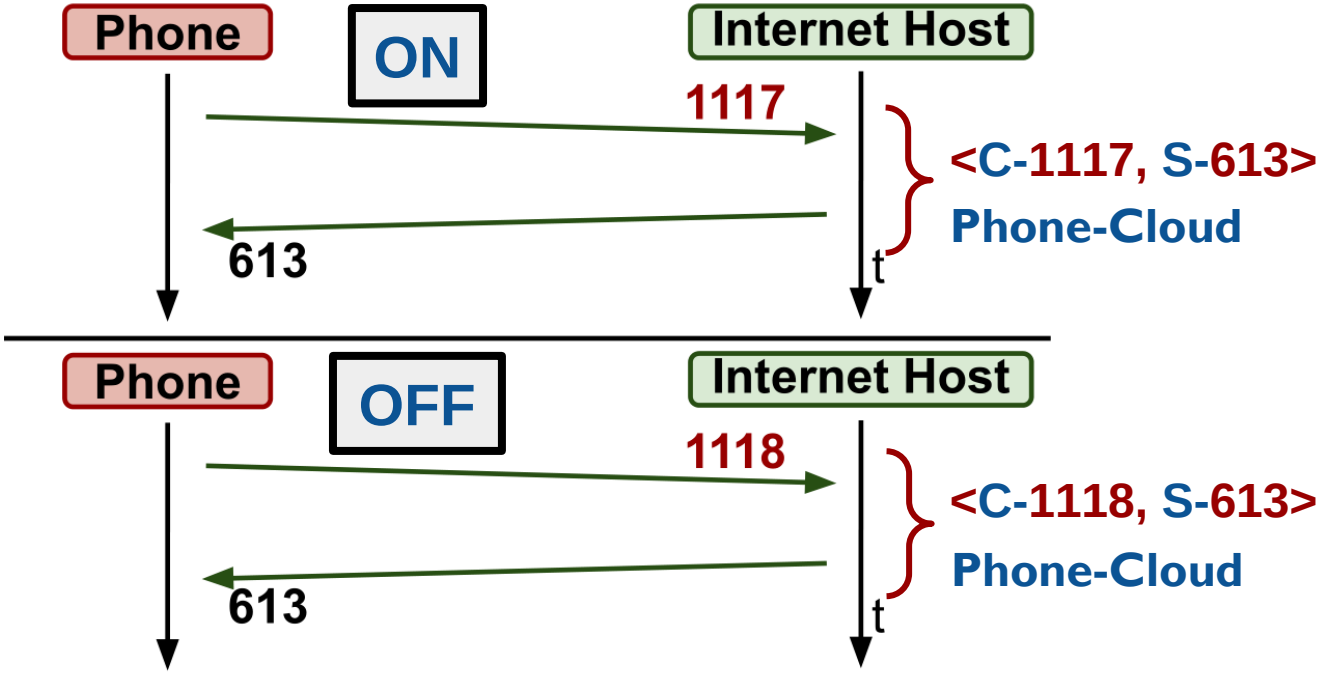
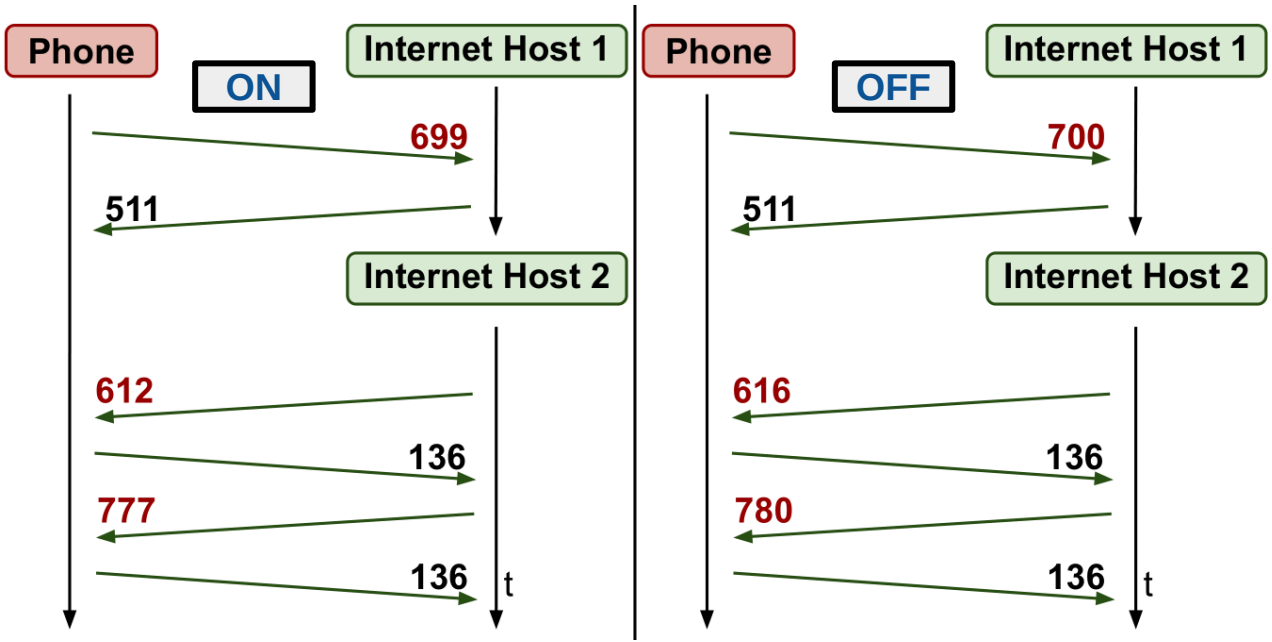


Ping-Pong in D-Link Plug



Ping-Pong in SmartThings Plug



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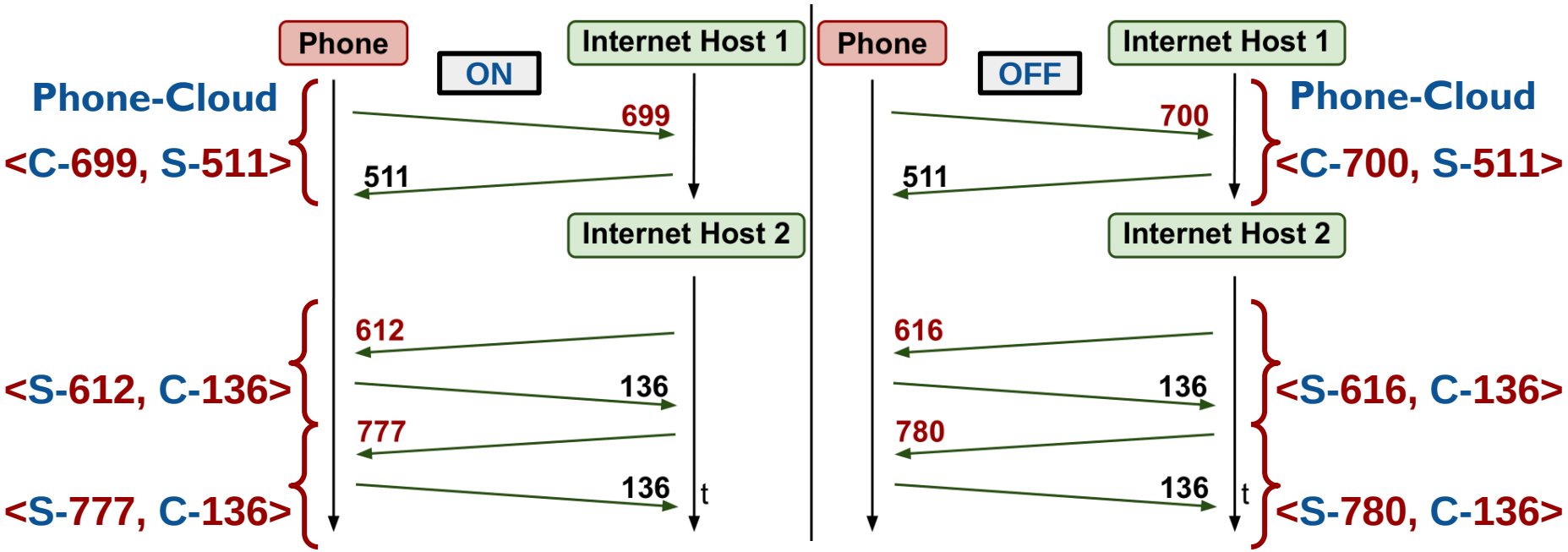

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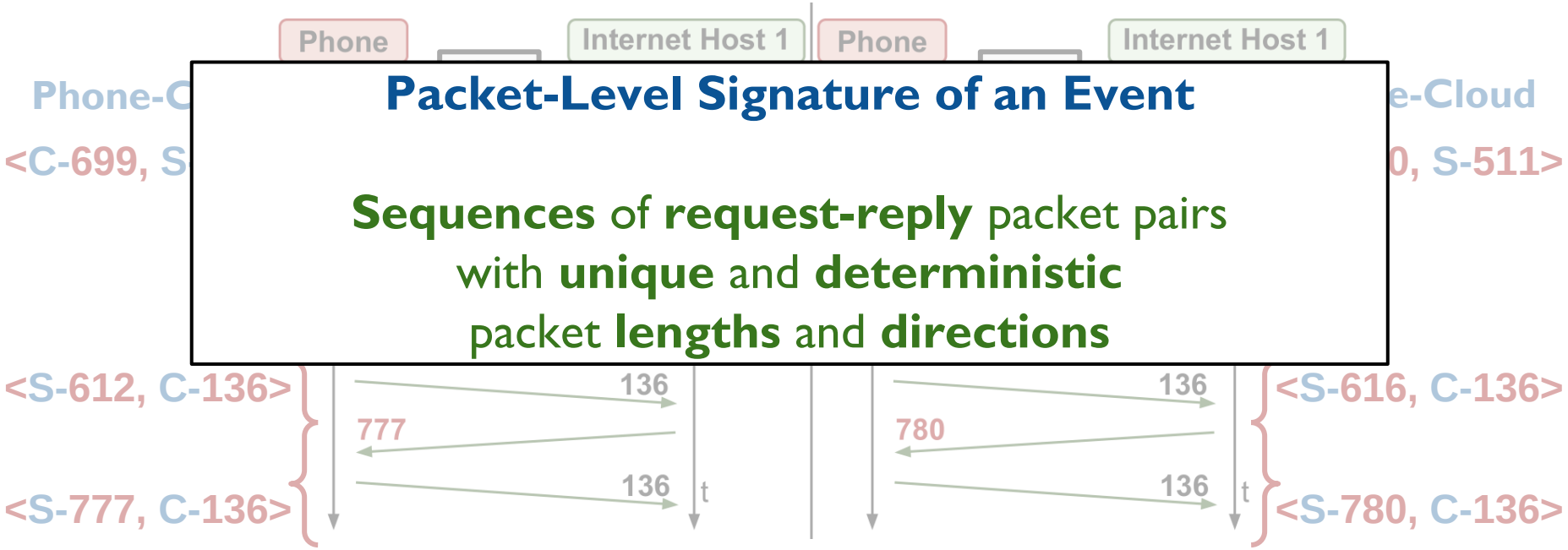

Research Questions

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- How **universal** are packet-level signatures?
- How **unique** are packet-level signatures?

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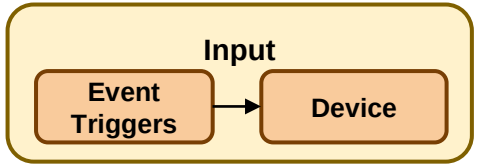
IV. Conclusion

Automated Extraction

- **Extract** these pairs
- Form **longest** possible **sequences**
- Use them as a **signature**

PingPong Training

The PingPong System



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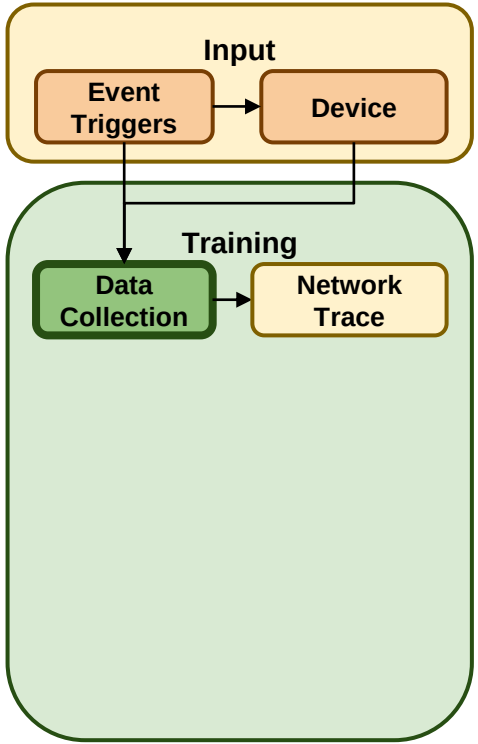

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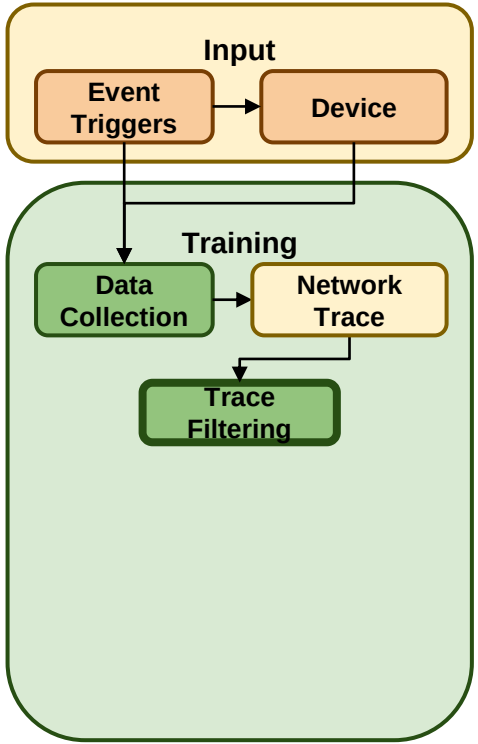

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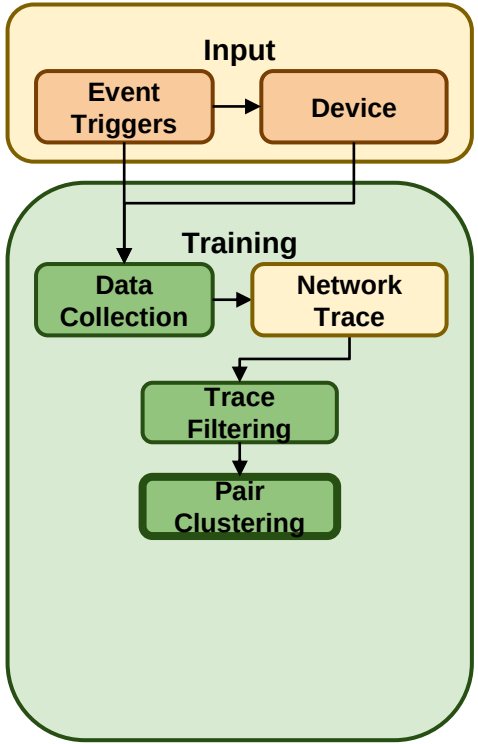

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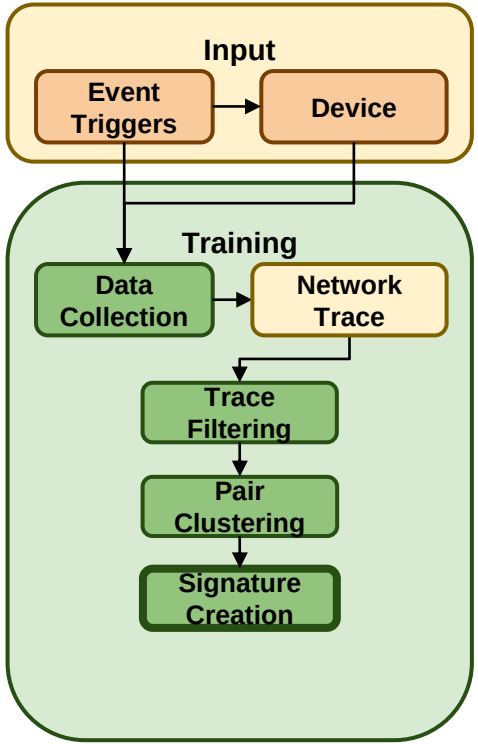

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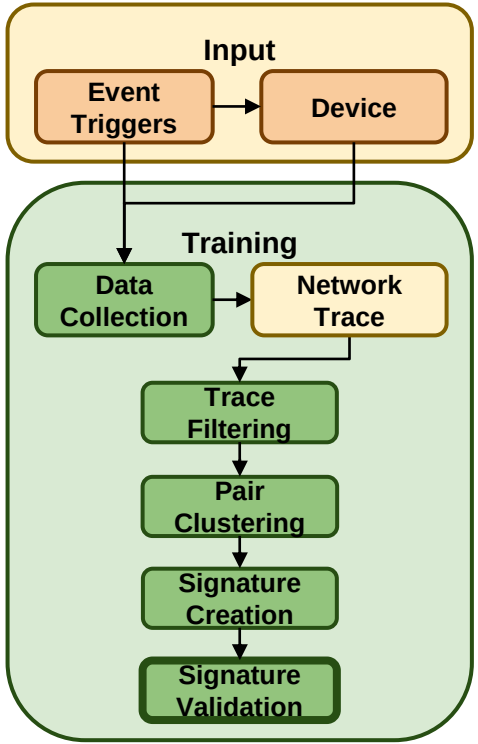

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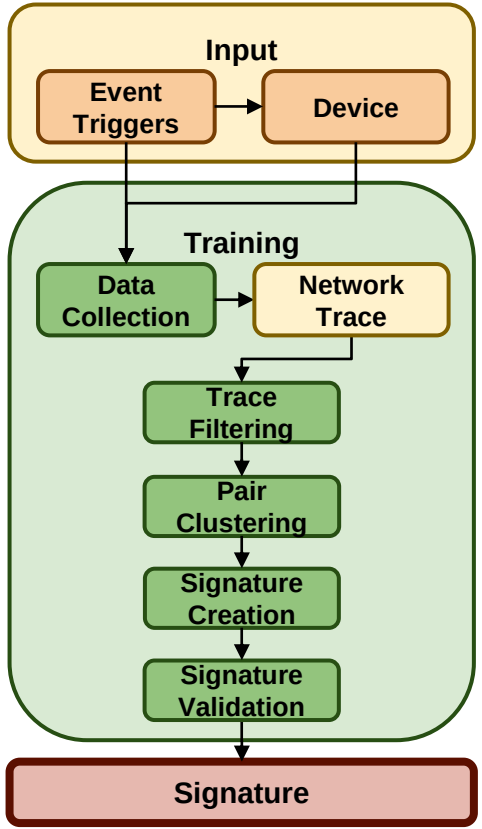

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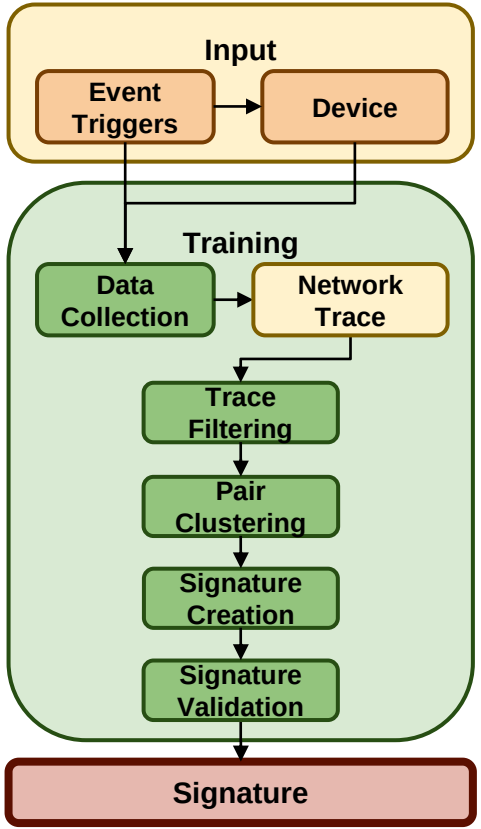

C-556 S-1293

PingPong Training

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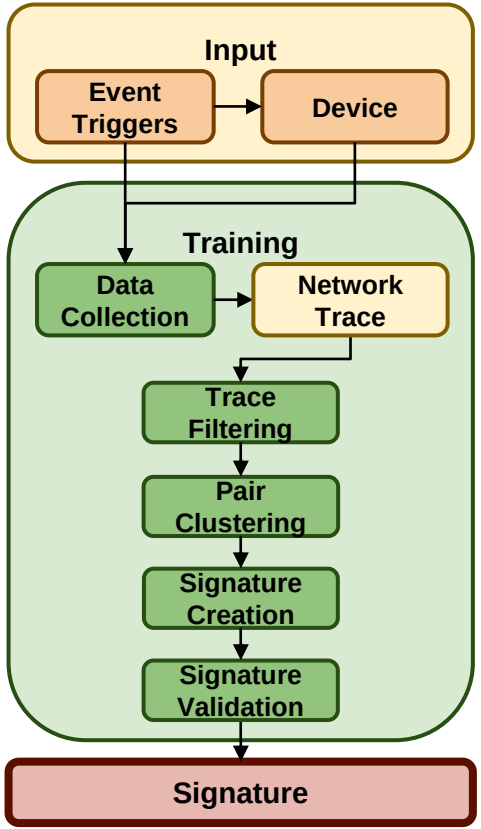

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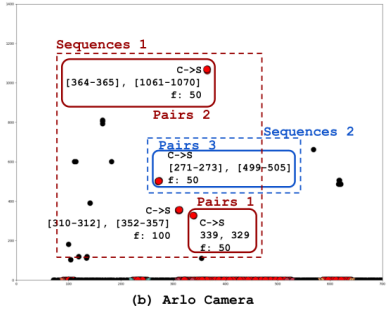
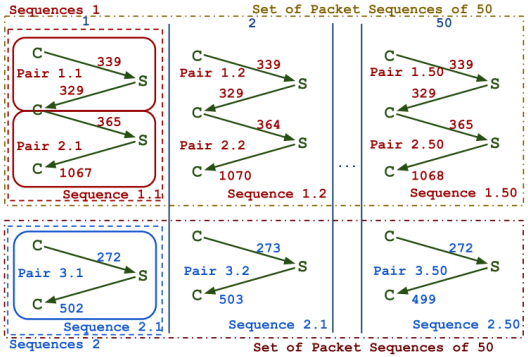
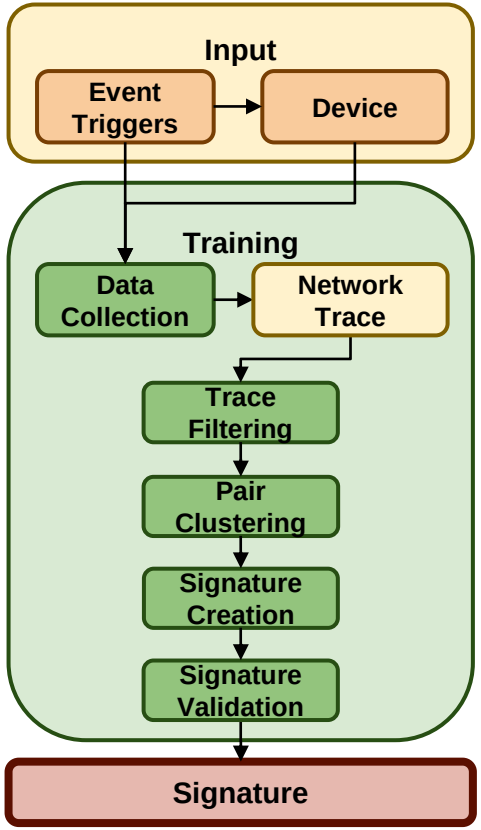




C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

PingPong Training

The PingPong System



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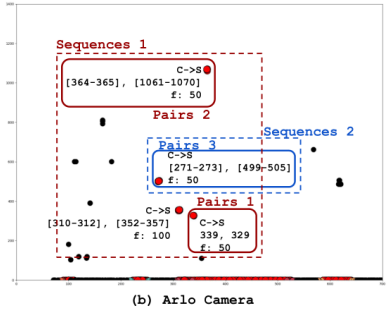

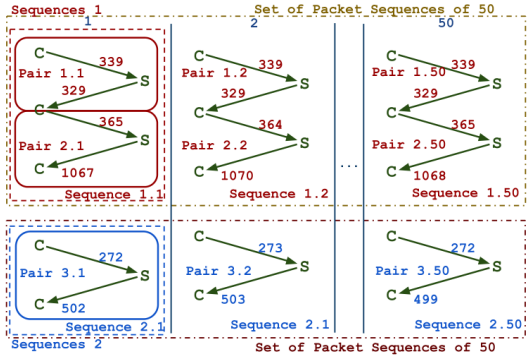

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Universal Signatures

- **Three** communications

Universal Signatures

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Universal Signatures

- **Three** communications
- **Two** adversaries
  - **WAN** and **Wi-Fi** sniffers

Universal Signatures

- **Three** communications
- **Two** adversaries
  - **WAN** and **Wi-Fi** sniffers
- Different triggers
  - **Local**-Phone

Universal Signatures

- Applies to many devices
  - Our corpus: **18** devices

Universal Signatures

- Applies to many devices
  - Our corpus: 18 devices

Device	Event	Signature	Communication	Matching (Per 100 Events)			
				WAN Snif.	FPR	Wi-Fi Snif.	FPR
Plugs							
Amazon plug	ON	**S1:** S-[443-445] **S2:** C-1099 S-235	Device-Cloud	98	0	99	0
	OFF	**S1:** S-[444-446] **S2:** C-1179 S-235 **S3:** C-1514 C-103 S-235					
WeMo plug	ON/OFF	**S1:** PH-259 PH-475 D-246	Phone-Device	-	-	100	0
WeMo Insight plug	ON/OFF	**S1:** PH-259 PH-475 D-246	Phone-Device	-	-	99	0
TP-Link plug	ON	**S1:** C-556 S-1293	Device-Cloud	99	0	-	-
	OFF	**S1:** C-557 S-[1294-1295]					
	ON	**S1:** PH-112 D-115 **S2:** C-556 S-1293	Phone-Device & Device-Cloud	-	-	99	0
	ON	**S1:** PH-112 D-115 **S2:** C-557 S-[1294-1295]					
D-Link plug	ON/OFF	**S1:** S-91 S-1227 C-784 **S2:** C-1052 S-647	Device-Cloud	95	0	95	0
	ON	**S1:** C-[1109-1123] S-613	Phone-Cloud	98	0	98	0
	OFF	**S1:** C-[1110-1124] S-613					
SmartThings plug	ON	**S1:** C-699 S-511 **S2:** S-777 C-136	Phone-Cloud	92	0	92	0
	OFF	**S1:** C-700 S-511 **S2:** S-780 C-136					

Universal Signatures

- Applies to many devices
  - Our corpus: 18 devices

Device	Event	Signature	Communication	Matching (Per 100 Events)			
				WAN Snif.	FPR	Wi-Fi Snif.	FPR
Light Bulbs							
Sengled light bulb	ON	**S1:** S-[217-218] C-[209-210] **S2:** C-430 **S3:** C-466	Device-Cloud	97	0	-	-
	OFF	**S1:** S-[217-218] C-[209-210] **S2:** C-430 **S3:** C-465					
	ON	**S1:** C-211 S-1063 **S2:** S-1277	Phone-Cloud	93	0	97	0
	OFF	**S1:** C-211 S-1063 S-1276					
	Intensity	**S1:** S-[216-220] C-[208-210]	Device-Cloud	99	2	-	-
	Intensity	**S1:** C-[215-217] S-[1275-1277]	Phone-Cloud	99	0	99	0
Hue light bulb	ON	**S1:** C-364 **S2:** D-88	Device-Cloud & Phone-Device	-	-	-	-
	OFF	**S1:** C-365 **S2:** D-88					
TP-Link light bulb	ON	**S1:** PH-198 D-227	Phone-Device	-	-	100	4
	OFF	**S1:** PH-198 D-244					
	Intensity	**S1:** PH-[240-242] D-[287-289]	Phone-Device	-	-	100	0
	Color	**S1:** PH-317 D-287	Phone-Device	-	-	100	0

Universal Signatures

- Applies to many devices
  - Our corpus: 18 devices

Device	Event	Signature	Communication	Matching (Per 100 Events)			
				WAN Snif.	FPR	Wi-Fi Snif.	FPR
Thermostats							
Nest thermostat	Fan ON	**S1:** C-[891-894] S-[830-834]	Phone-Cloud	93	0	93	1
	Fan OFF	**S1:** C-[858-860] S-[829-834]					
Ecobee thermostat	HVAC Auto	**S1:** S-1300 C-640	Phone-Cloud	100	0	99	0
	HVAC OFF	**S1:** C-1299 C-640					
	Fan ON	**S1:** S-1387 C-640	Phone-Cloud	100	0	100	0
	Fan Auto	**S1:** C-1389 C-640					
Sprinklers							
Rachio sprinkler	Quick Run	**S1:** S-267 C-155	Device-Cloud	100	0	100	0
	Stop	**S1:** C-496 C-155 C-395					
	Standby/Active	**S1:** S-299 C-155 C-395	Device-Cloud	100	0	100	0
Blossom sprinkler	Quick Run	**S1:** C-326 **S2:** C-177 S-505	Device-Cloud	96	0	96	0
	Stop	**S1:** C-326 **S2:** C-177 S-458 **S3:** C-238 C-56 S-388					
	Quick Run	**S1:** C-649 S-459 C-574 S-507 **S2:** S-[135-139]	Phone-Cloud	93	0	93	0
	Stop	**S1:** C-617 S-431					
	Hibernate	**S1:** C-621 S-493	Phone-Cloud	95	0	93	0
	Active	**S1:** C-622 S-494 **S2:** S-599 C-566 S-554 C-566					

Universal Signatures

- Applies to many devices
  - Our corpus: 18 devices

Device	Event	Signature	Communication	Matching (Per 100 Events)			
				WAN Snif.	FPR	Wi-Fi Snif.	FPR
Home Security Devices							
Ring alarm	Arm	**S1:** S-99 S-254 C-99 S-[181-183] C-99	Device-Cloud	98	0	95	0
	Disarm	**S1:** S-99 S-255 C-99 S-[181-183] C-99					
Arlo camera	Stream ON	**S1:** C-[338-339] S-[326-329] C-[364-365] S-[1061-1070] **S2:** C-[271-273] S-[499-505]	Phone-Cloud	99	2	98	3
	Stream OFF	**S1:** C-[445-449] S-442					
D-Link siren	ON	**S1:** C-1076 S-593	Phone-Cloud	100	0	98	0
	OFF	**S1:** C-1023 S-613					
Kwikset door lock	Lock	**S1:** C-699 S-511 **S2:** S-639 C-136	Phone-Cloud	100	0	100	0
	Unlock	**S1:** C-701 S-511 **S2:** S-647 C-136					
Others							
Roomba robot	Clean	**S1:** S-[1014-1015] C-105 S-432 C-105	Phone-Cloud	91	0	94	0
	Back-to-station	**S1:** S-440 C-105 S-[1018-1024] C-105					

Universal Signatures

- Applies to many devices
  - Our corpus: **18** devices

Universal Signatures

- Applies to many devices
  - Our corpus: **18** devices
  - Public dataset Mon(IoT)r
    - Extraction for **21 new** devices

Universal Signatures

- Applies to ma
  - Our corpus:
  - Public dataset
    - Extraction fo

Device	Event	Signature	Duration (ms)
Cameras			
Amazon camera	Watch	**S1:** S-[627-634] C-[1229-1236]	203 / 261 / 476
Blink hub	Watch	**S1:** S-199 C-135 C-183 S-135	99 / 158 / 275
	Photo	**S1:** S-199 C-135 C-183 S-135	87 / 173 / 774
Lefun camera	Photo	**S1:** S-258 C-[206-210] S-386 C-206 **S2:** C-222 S-198 C-434 S-446 C-462 S-194 C-1422 S-246 C-262 **S3:** C-182	17,871 / 19,032 / 20,358
	Recording	**S1:** S-258 C-210 S-386 C-206 **S2:** C-222 S-198 C-434 S-446 C-462 S-194	13,209 / 15,279 / 16,302
	Watch	**S1:** S-258 C-210 S-386 C-206 **S2:** C-222 S-198 C-434 S-446 C-462 S-194	14,151 / 15,271 / 16,131
Microseven camera	Watch	**S1:** D-242 PH-118	1 / 5 / 38
ZModo doorbell	Photo	**S1:** C-94 S-88 S-282 C-240 / **S1:** S-282 C-240 C-94 S-88	1,184 / 8,032 / 15,127
	Recording	**S1:** C-94 S-88 S-282 C-240 / **S1:** S-282 C-240 C-94 S-88	305 / 7,739 / 15,137
	Watch	**S1:** C-94 S-88 S-282 C-240 / **S1:** S-282 C-240 C-94 S-88	272 / 7,679 / 15,264
Light Bulbs			
Flex light bulb	ON/OFF	**S1:** PH-140 D-[346-347]	4 / 44 / 78
	Intensity	**S1:** PH-140 D-346	4 / 18 / 118
	Color	**S1:** PH-140 D-346	4 / 12 / 113
Wink hub	ON/OFF	**S1:** PH-204 D-890 PH-188 D-113	43 / 55 / 195
	Intensity	**S1:** PH-204 D-890 PH-188 D-113	43 / 50 / 70
	Color	**S1:** PH-204 D-890 PH-188 D-113	43 / 55 / 106
Voice Command Devices			
Allure speaker	Audio ON/OFF	**S1:** C-658 C-412	89 / 152 / 196
	Volume	**S1:** C-[594-602] **S2:** C-[92-100]	217 / 4,010 / 11,005
Amazon Echo Dot	Voice	**S1:** C-491 S-[148-179]	1 / 23 / 61
	Volume	**S1:** C-[283-290] C-[967-979] **S2:** C-[197-200] C-[147-160]	1,555 / 2,019 / 2,423
Amazon Echo Plus	Audio ON/OFF	**S1:** S-100 C-100	1 / 5 / 28
	Color	**S1:** S-100 C-100	1 / 4 / 18
	Intensity	**S1:** S-100 C-100	1 / 4 / 11
	Voice	**S1:** C-[761-767] S-437 **S2:** C-172 S-434	1,417 / 1,871 / 2,084
	Volume	**S1:** C-172 S-434	2 / 13 / 40
Amazon Echo Spot	Audio ON/OFF	**S1:** S-100 C-100	1 / 8 / 233
	Voice	**S1:** C-246 S-214 **S2:** C-172 S-434	1,220 / 1,465 / 1,813
	Volume	**S1:** C-246 S-214 **S2:** C-172 S-434	1,451 / 1,709 / 1,958
Google Home	Voice	**S1:** C-1434 S-136	9 / 61 / 132
	Volume	**S1:** C-1434 S-[124-151] **S2:** C-521 S-[134-135]	8,020 / 9,732 / 10,002
Google Home Mini	Voice	**S1:** C-1434 S-[127-153]	1 / 29 / 112
	Volume	**S1:** C-1434 S-[135-148]	5 / 47 / 123
Harman Kardon Invoke speaker	Voice	**S1:** S-1494 S-277 C-1494 **S2:** S-159 S-196 C-1494	2,199 / 2,651 / 3,762
	Volume	**S1:** S-159 S-196 C-1418 C-1320 S-277 **S2:** S-196 C-[404-406]	223 / 567 / 793
Smart TVs			
Fire TV	Menu	**S1:** C-468 S-323	16 / 18 / 20
LG TV	Menu	**S1:** PH-204 D-1368 PH-192 D-117	43 / 90 / 235
Roku TV	Remote	**S1:** PH-163 D-[163-165] **S2:** PH-145 D-410 **S2:** PH-147 D-113	578 / 1,000 / 1,262
Samsung TV	Menu	**S1:** PH-[237-242] D-274	2 / 7 / 15
Other Types of Devices			
Honeywell thermostat	ON	**S1:** S-635 C-256 C-795 S-139 C-923 S-139	1,091 / 1,248 / 1,420
	OFF	**S1:** S-651 C-256 C-795 S-139 C-923 S-139	
	Set	**S1:** C-779 S-139	86 / 102 / 132
Insteon hub	ON/OFF	**S1:** S-491 C-623 **S2:** C-784 C-234 S-379	76 / 100 / 1,077
Samsung fridge	Set	**S1:** C-116 S-112	177 / 185 / 185
	View Inside	**S1:** C-116 S-112	177 / 197 / 563

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Universal Signatures

- Applies to many devices
  - Our corpus: **18** devices
  - Public dataset Mon(IoT)r
    - Extraction for **21 new** devices
    - Comparison for **5 common** devices

Universal Signatures

- **Three** communications
- **Two** adversaries
  - **WAN** and **Wi-Fi** sniffers
- Different triggers
  - **Local**-Phone

Universal Signatures

- **Three** communications
- **Two** adversaries
  - **WAN** and **Wi-Fi** sniffers
- Different triggers
  - **Local**-Phone
  - **Remote**-Phone, and
  - Home **Automation**

Universal Signatures

- Three communications
- Two a
  - WA
- Differe
  - Loc
  - Ren
  - Hom

Device	Event	Device-Cloud Signature	Matching (Per 100 Events)			
			WAN Sniffer	FPR	Wi-Fi Sniffer	FPR
Plugs						
WeMo plug	ON/OFF	**S1:** S-146 **S2:** C-210 S-134 S-286 C-294	100	0	100	0
WeMo Insight plug	ON	**S1:** S-146 **S2:** C-210 S-134 S-286 C-294	99	0	94	0
	OFF	**S1:** S-146 **S2:** C-210 S-134 S-350 C-294				
TP-Link plug	ON	**S1:** C-592 S-1234 S-100	100	0	100	0
	OFF	**S1:** C-593 S-1235 S-100				
D-Link plug	ON/OFF	**S1:** C-256 **S2:** C-1020 S-647	93	1	93	1
Light Bulbs						
Hue light bulb	ON	**S1:** S-[227-229] C-[857-859] C-365	99	1	-	-
	OFF	**S1:** S-[227-230] C-[857-860] C-366				
	Intensity	**S1:** S-[237-240] C-[895-899] **S2:** C-[378-379]	97	0	-	-
TP-Link light bulb	ON	**S1:** S-[348-349] C-[399-400]	100	0	100	0
	OFF	**S1:** S-[348-349] C-[418-419]				
	Intensity	**S1:** S-[438-442] C-[396-400]	100	0	99	0
	Color	**S1:** S-[386-388] C-[397-399]	99	0	97	0
Others						
Rachio sprinkler	Quick Run	**S1:** S-267 C-155	95	3	95	5
	Stop	**S1:** C-661 **S2:** C-155				
Arlo camera	Start Recording	**S1:** C-704 S-215	100	0	99	0
D-Link siren	ON	**S1:** S-[989-1005] C-616 **S2:** C-216	99	1	98	1
			98.4	0.5	97.5	0.7

Universal Signatures

- **Three** communications
- **Two** adversaries
  - **WAN** and **Wi-Fi** sniffers
- Different triggers
  - **Local**-Phone
  - **Remote**-Phone, and
  - Home **Automation**
- Matching with recall **> 97%**

Unique Signatures

- Distinguish
  - **Device type**
  - **Event type:** binary and non-binary
  - Same-vendor devices

Unique Signatures

- Distinguish
  - Devic
  - Even
  - Same-

Device	Model	Event	Signature
Existing TP-Link Devices			
TP-Link plug	HS-110	ON	∗**S1:** PH-172 D-115 **S2:** C-592 S-1234 S-100
		OFF	∗**S1:** PH-172 D-115 **S2:** C-593 S-1235 S-100
TP-Link light bulb	LB-130	ON	∗**S1:** PH-258 D-288
		OFF	∗**S1:** PH-258 D-305
		Intensity	**S1:** PH-[240-242] D-[287-289]
		Color	**S1:** S1: PH-317 D-287
Newly Added TP-Link Devices			
TP-Link two-outlet plug	HS-107	ON	**S1:** PH-219 D-103 **S2:** C-300 C-710 S-1412 S-88
		OFF	**S1:** PH-219 D-103 **S2:** C-300 C-711 S-1413 S-88
TP-Link power strip	HS-300	ON	**S1:** PH-219 D-103 **S2:** C-301 C-1412 S-[1405-1406] S-88
		OFF	**S1:** PH-219 D-103 **S2:** C-301 C-1413 S-[1406-1407] S-88
TP-Link white light bulb	KL-110	ON	**S1:** S-[414-415] C-[331-332] **S2:** C-648 S-[1279-1280] S-88
		OFF	**S1:** S-[414-415] C-[350-351] **S2:** C-649 S-[1280-1281] S-88
		Intensity	**S1:** S-[479-483] C-[329-332] **S2:** C-[654-656] S-[1285-1288] S-88
TP-Link camera	KC-100	ON	**S1:** PH-256 D-162 PH-624 D-256 PH-72 D-111 PH-608 D-371 PH-97 **S2:** C-1288 S-[1161-1162] S-100
		OFF	**S1:** PH-256 D-162 PH-624 D-256 PH-72 D-111 PH-614 D-371 PH-97 **S2:** C-1289 S-[1162-1163] S-100

Unique Signatures

- Distinguish
  - **Device type**
  - **Event type:** binary and non-binary
  - Same-vendor devices
- Negative control experiment
  - Three public datasets: **>440 million** packets
    - YourThings, UNSW, UNB
  - FPR: **one FP** per **40 million packets**

Packet-Level Signatures

- Can distinguish event types ✓

Packet-Level Signatures

- Can distinguish event types ✓
- Minimal set of traffic features ✓

Packet-Level Signatures

- Can distinguish event types ✓
- Minimal set of traffic features ✓
- Two adversaries ✓

Packet-Level Signatures

- Can distinguish event types ✓
- Minimal set of traffic features ✓
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- Applicable to many devices ✓

Packet-Level Signatures

- Can distinguish event types ✓
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- Two adversaries ✓
- Applicable to many devices ✓
- Resilient to traffic shaping & VPN encryption ✓
- Defended against by packet padding ✓

Packet-Level Signatures

- Can distinguish event types ✓
- Minimal set of traffic features ✓
- Two adversaries ✓
- Applicable to many devices ✓
- Resilient to traffic shaping & VPN encryption ✓
- Defended against by packet padding ✓
- Profiling and network monitoring ✓

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Limitations

- Need device to train
- Signatures may vary over time
- Apply to **95%** of devices
  - UDP-based
  - Repetitive pairs for an event

Outline

I. Background and Problem Statement
II. Key Observation: Packet-Level Signatures
III. The PingPong System
IV. Conclusion

Conclusions

- Packet-level signatures
  - **Request-reply** pattern
  - Packet **lengths** and **directions**
- Automation: **PingPong**
  - Extraction and detection
- Signatures are **universal** and **unique**

Thank You!

- Paper
  https://www.ndss-symposium.org/ndss-paper/packet-level-signatures-for-smart-home-devices/
- Software and datasets
  http://plrg.ics.uci.edu/pingpong/

Additional Slides

Signature Variations

- Signatures with no variation
- Signatures with ranges
- Signatures that vary
  - Signature evolution
  - Signatures that vary in certain packets
    - App's username and password

C-556 S-1293

C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

C-556 S-1293 2018

C-592 S-1234 S-100 } 2019

C-605 S-1213 S-100 }

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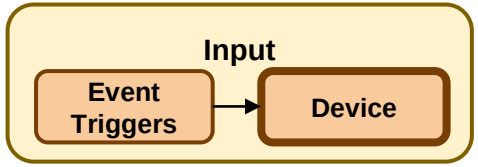
PingPong Training

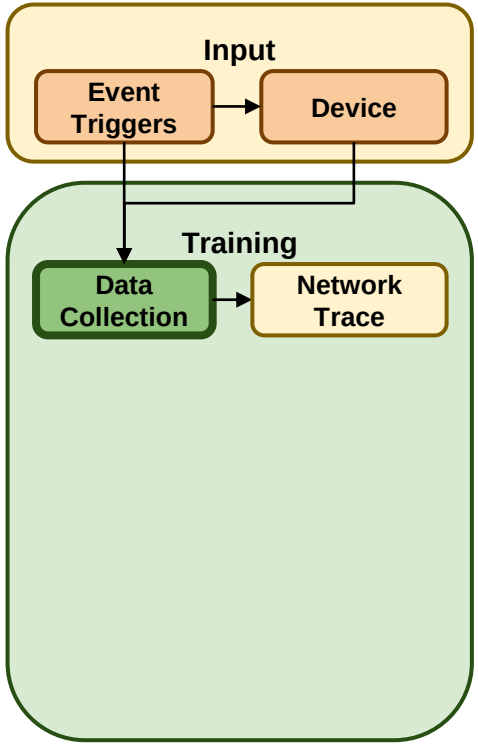
The PingPong System



Toggle ON for TP-Link Plug

PingPong Training

The PingPong System



Toggle ON for TP-Link Plug

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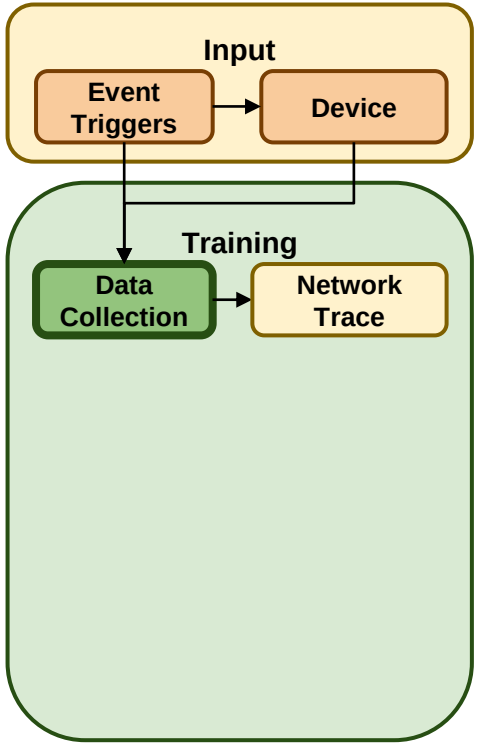
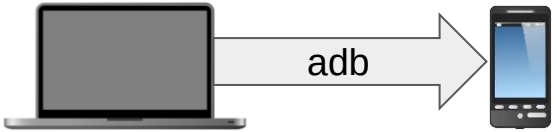
PingPong Training

The PingPong System

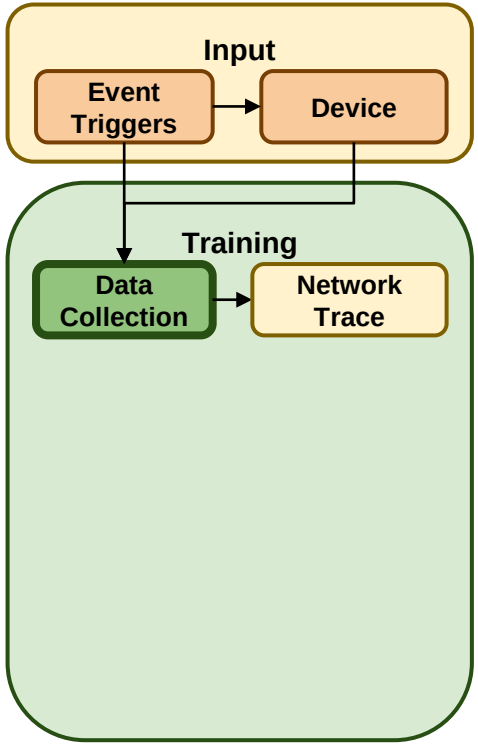


Toggle ON for TP-Link Plug

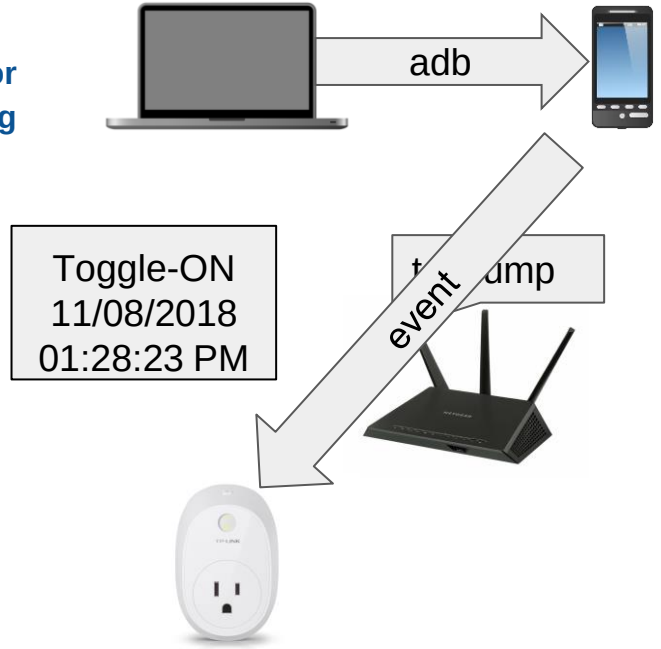


PingPong Training

The PingPong System



Toggle ON for TP-Link Plug



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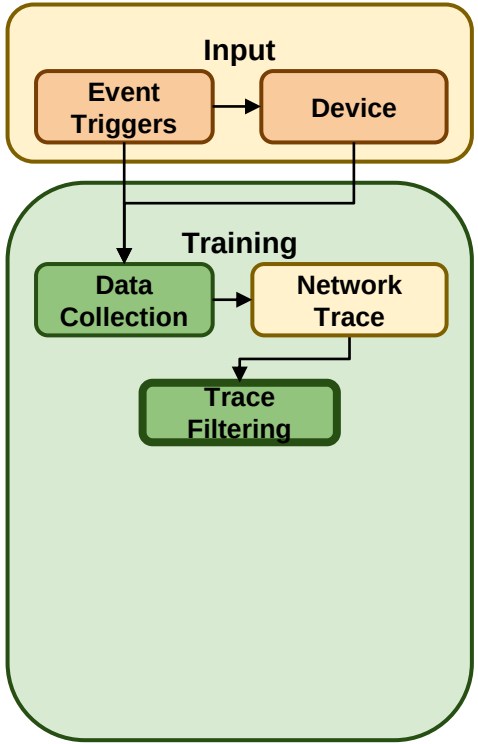
PingPong Training

The PingPong System



Toggle ON for TP-Link Plug

PCAP file

...

… C-123 S-456 … C-234 S-567
… C-345 S-678 ...

… C-556 S-1293 ... C-238 S-826
… C-129 S-123 ...

… C-123 S-456 … C-234 S-567
… C-345 S-678 …

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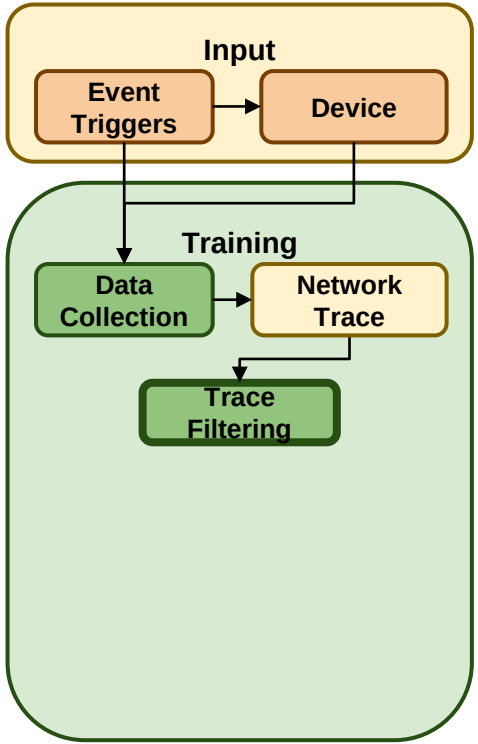
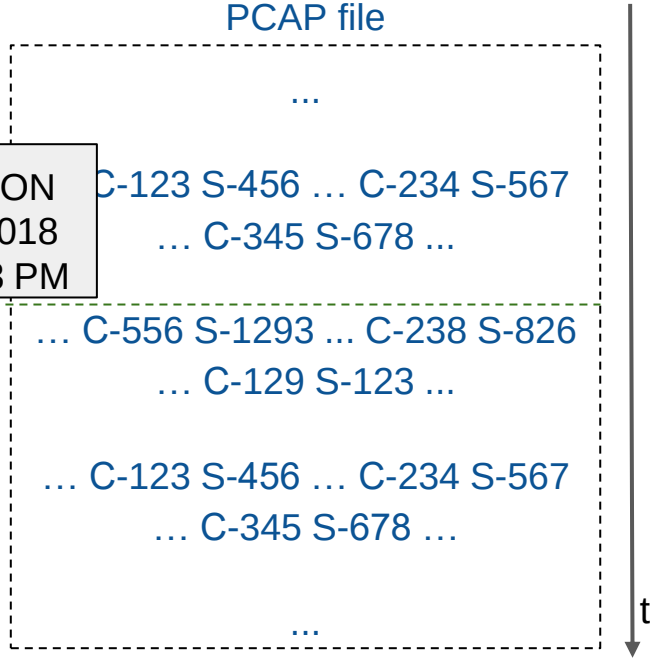
PingPong Training

The PingPong System

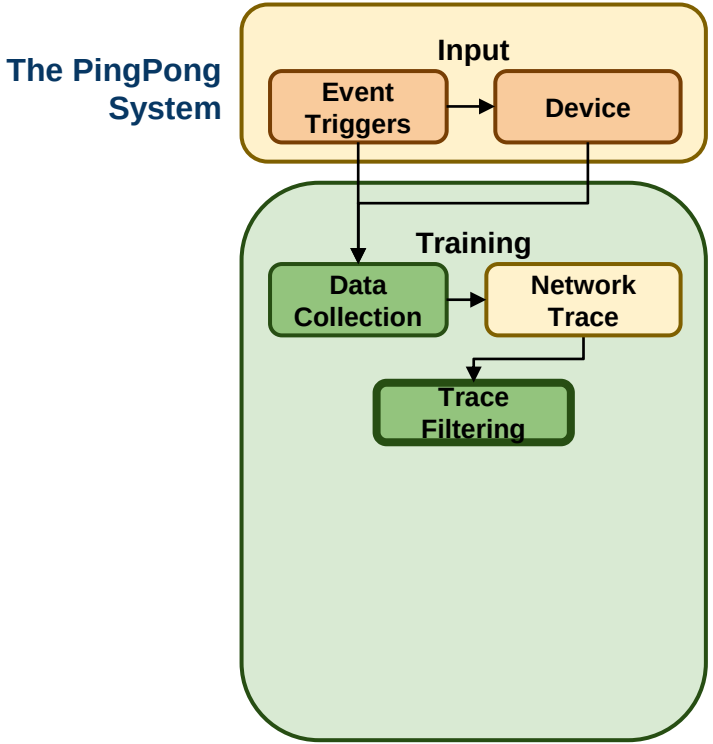


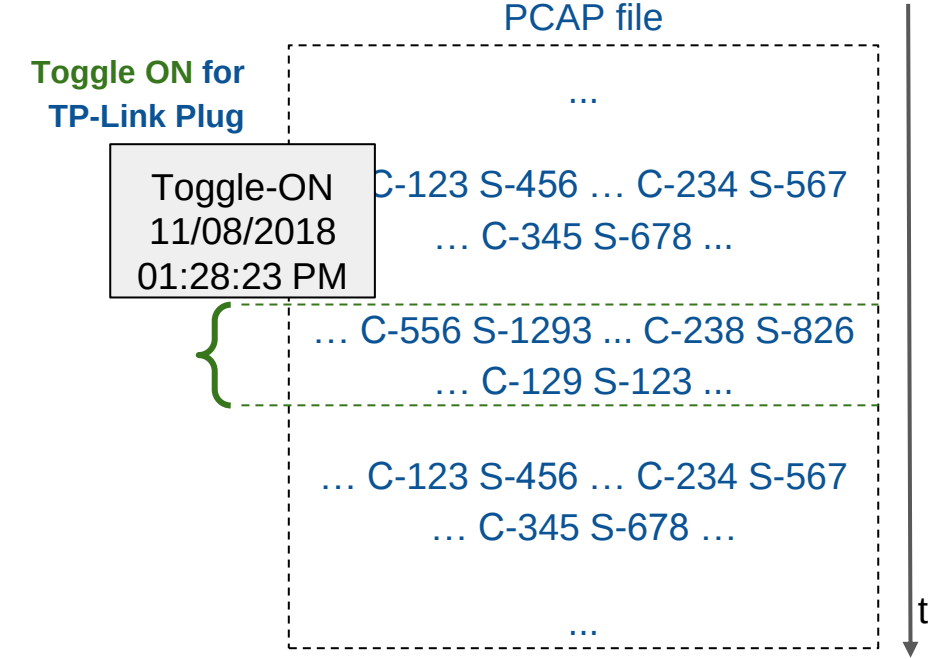
Toggle ON for TP-Link Plug

Toggle-ON
11/08/2018
01:28:23 PM



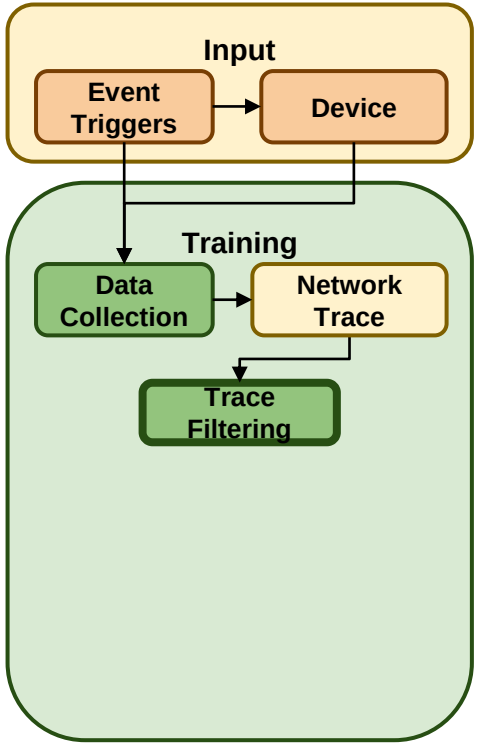
PingPong Training





PingPong Training

The PingPong System

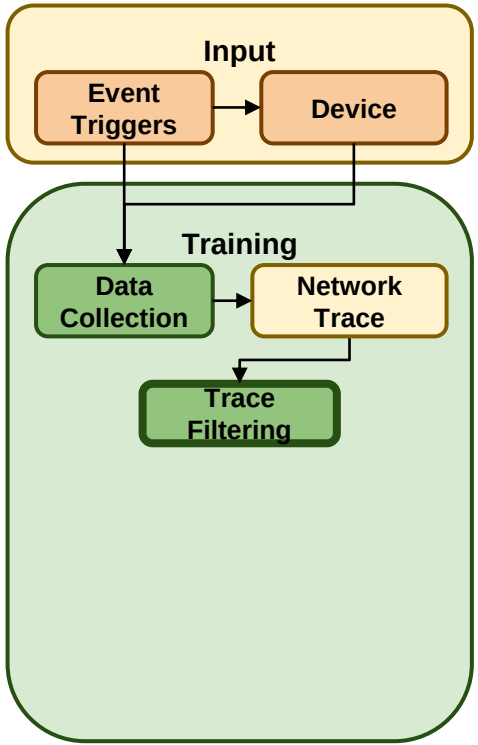


Toggle ON for TP-Link Plug

… C-556 S-1293 ... C-238 S-826
… C-129 S-123 ...

PingPong Training

The PingPong System



Toggle ON for TP-Link Plug

… C-556 S-1293 ... C-238 S-826
… C-129 S-123 ...

TCP Conn.1 … C-556 S-1293 ...

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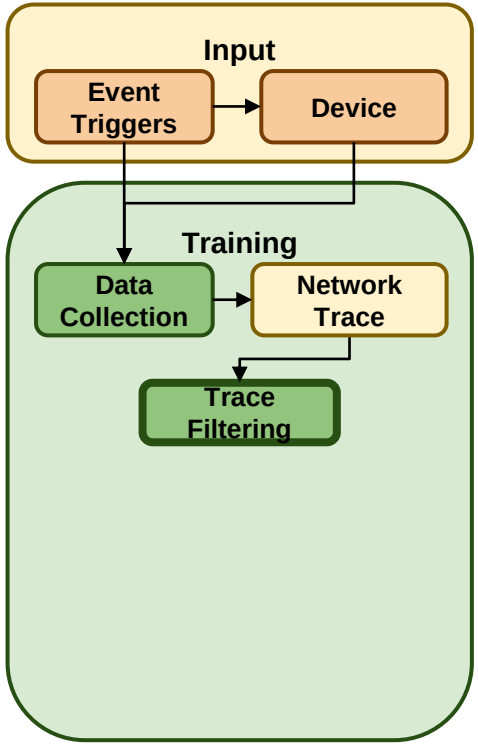
PingPong Training

The PingPong System



Toggle ON for TP-Link Plug

… C-556 S-1293 ... C-238 S-826 … C-129 S-123 ...

TCP Conn.1 … C-556 S-1293 ...

TCP Conn.2 … C-238 S-826 ...

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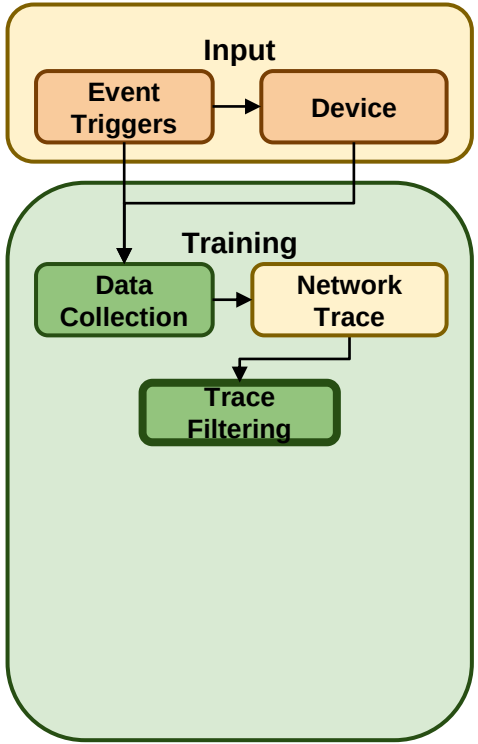
PingPong Training

The PingPong System



Toggle ON for TP-Link Plug

… C-556 S-1293 … C-238 S-826 … C-129 S-123 …

TCP Conn.1 … C-556 S-1293 ...

TCP Conn.2 … C-238 S-826 ...

TCP Conn.3 … C-129 S-123 ...

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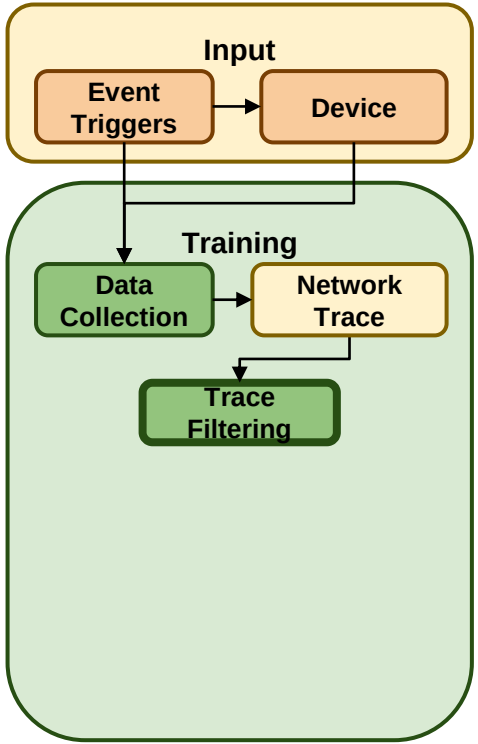
PingPong Training

The PingPong System



Toggle ON for TP-Link Plug

… C-556 S-1293 ... C-238 S-826 … C-129 S-123 ...

Packet Pairs

<...,...> <C-556, S-1293> <...,...>

<...,...> <C-238, S-826> <...,...>

<...,...> <C-129, S-123> <...,...>

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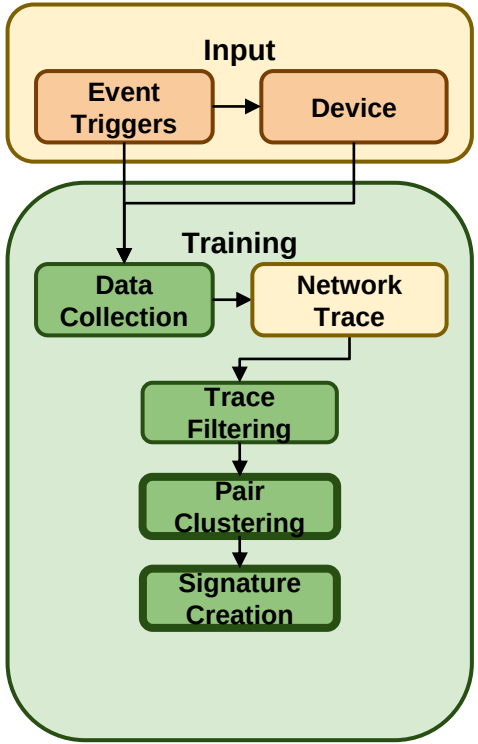
PingPong Training

The PingPong System



Toggle ON for TP-Link Plug

Packet Pairs

<...,...> <C-556, S-1293> <...,...>

<...,...> <C-238, S-826> <...,...>

<...,...> <C-129, S-123> <...,...>

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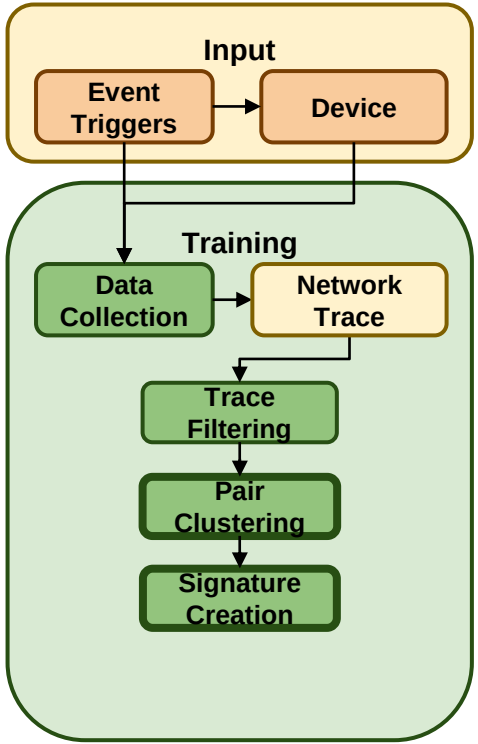
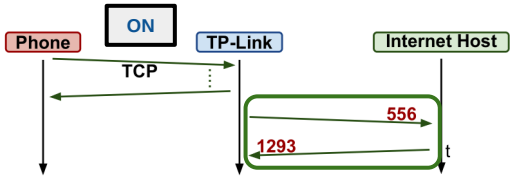
PingPong Training

The PingPong System



Toggle ON for TP-Link Plug



Packet Pairs

<...,...> <C-556, S-1293> <...,...>

<...,...> <C-238, S-826> <...,...>

<...,...> <C-129, S-123> <...,...>

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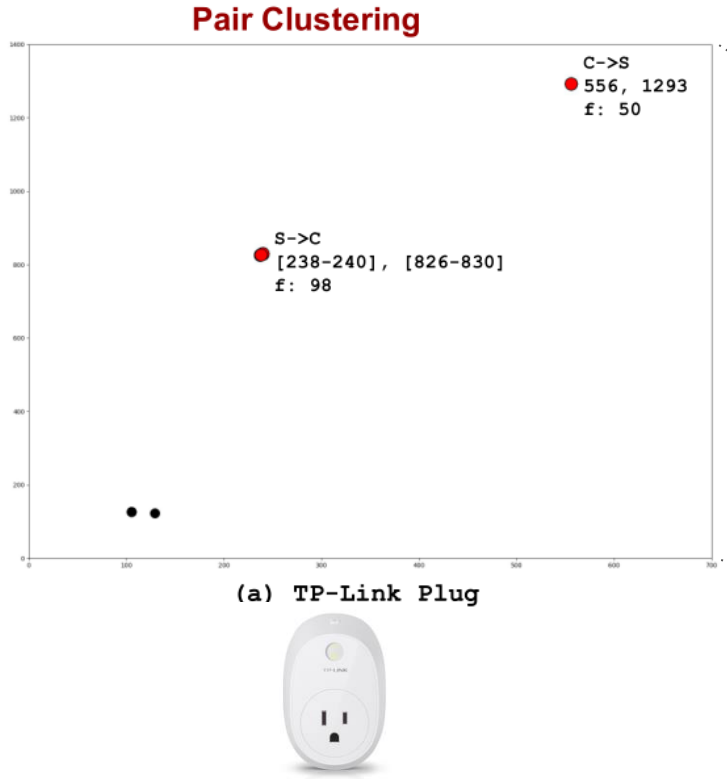
PingPong Training



<...,...> <C-556, S-1293> <...,...>

<...,...> <C-238, S-826> <...,...>

<...,...> <C-129, S-123> <...,...>

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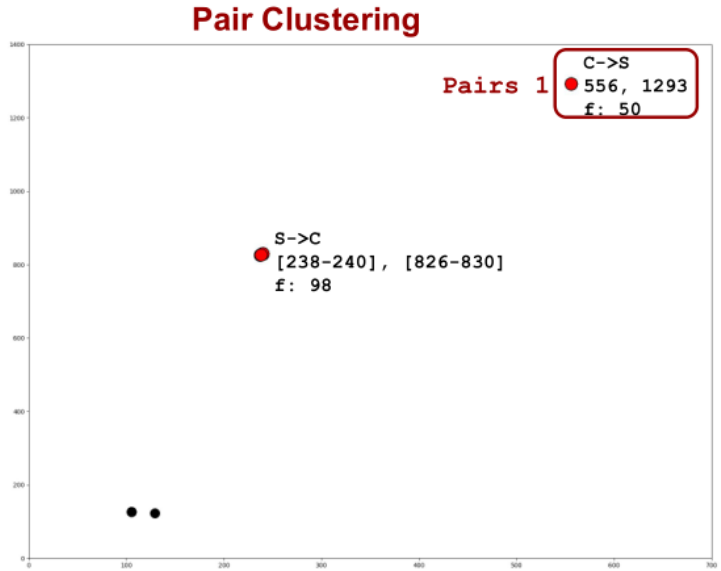
PingPong Training



(a) TP-Link Plug

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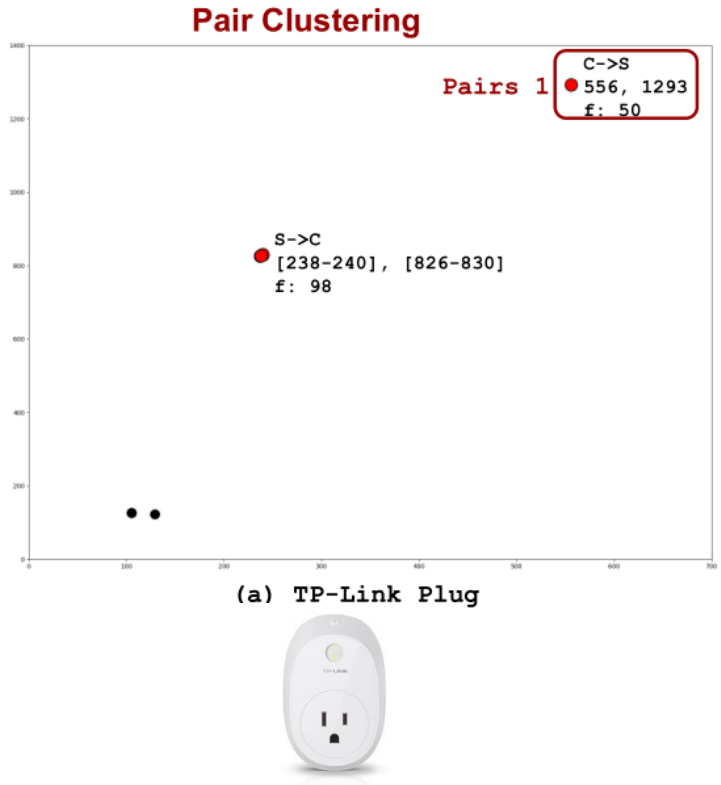
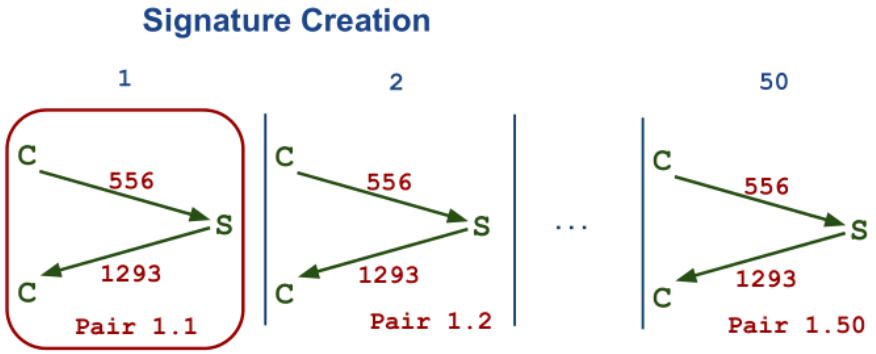
PingPong Training





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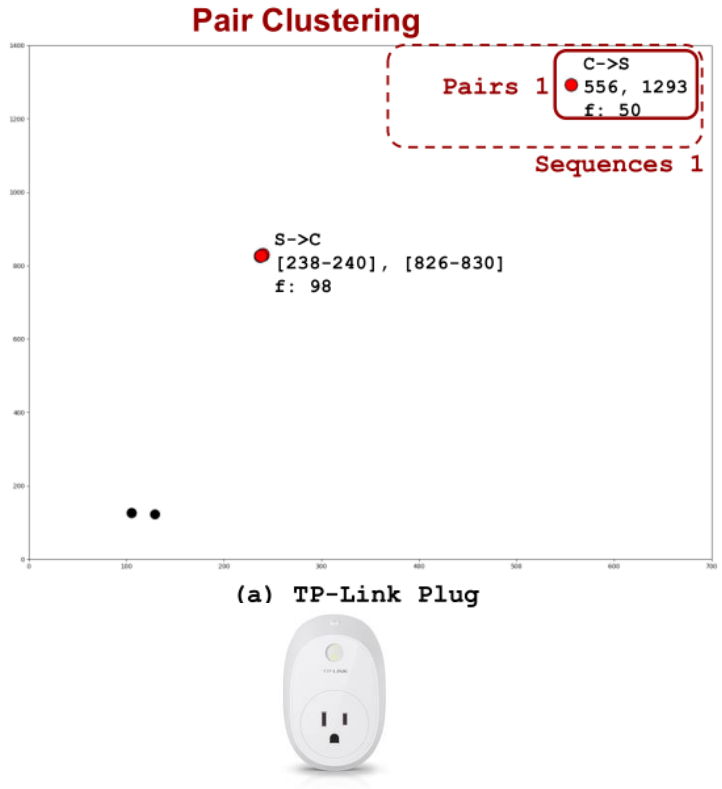
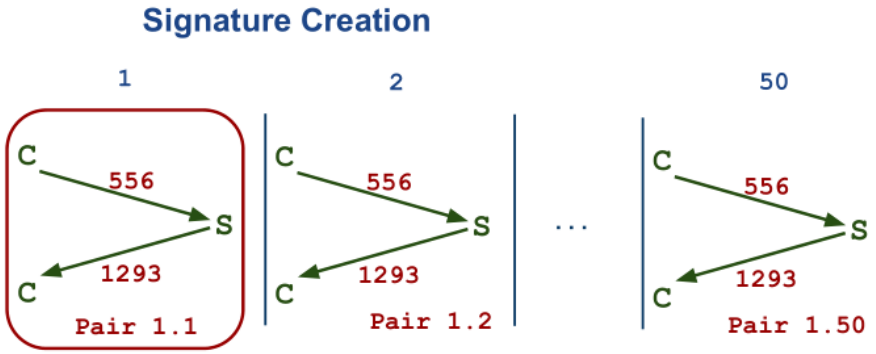
PingPong Training





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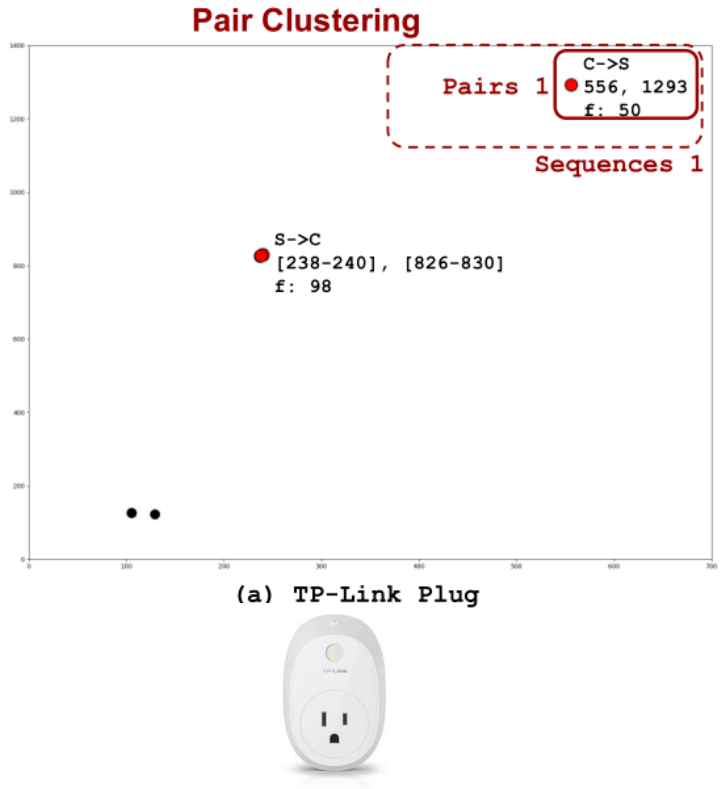
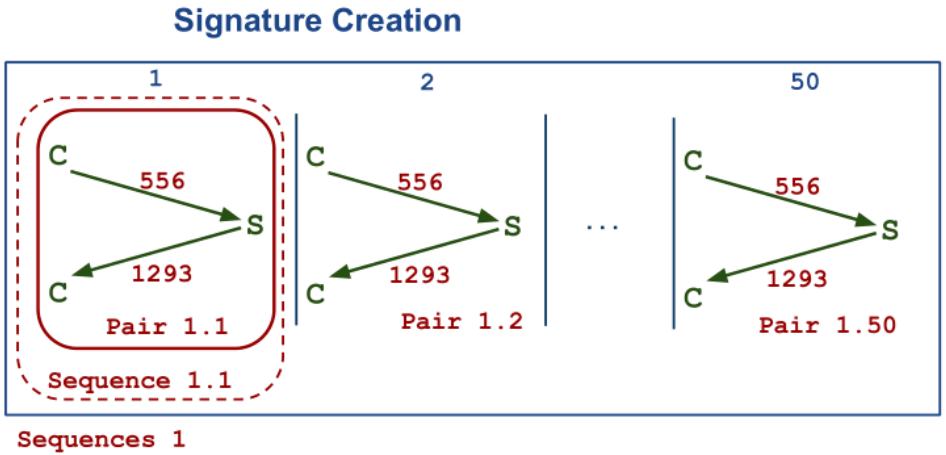
PingPong Training





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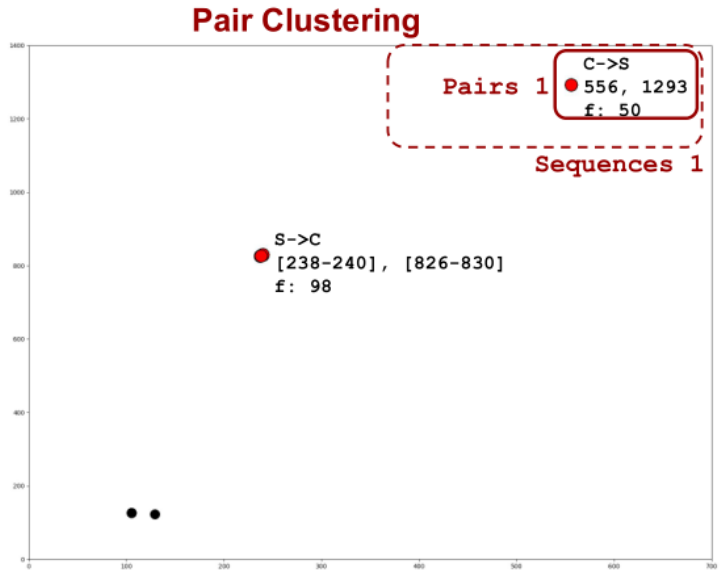
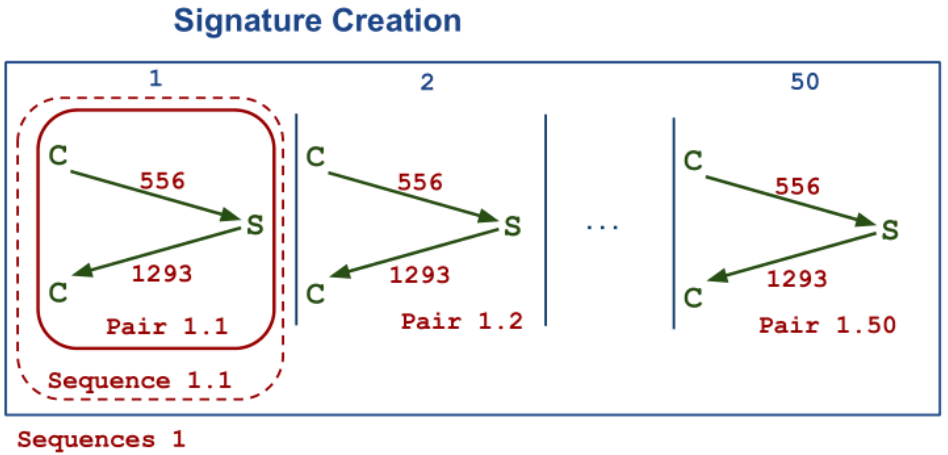
PingPong Training



(a) TP-Link Plug



C-556 S-1293

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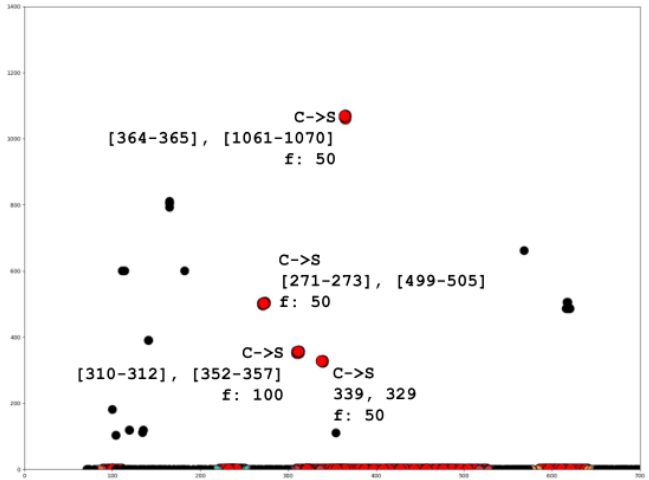
PingPong Training



(b) Arlo Camera

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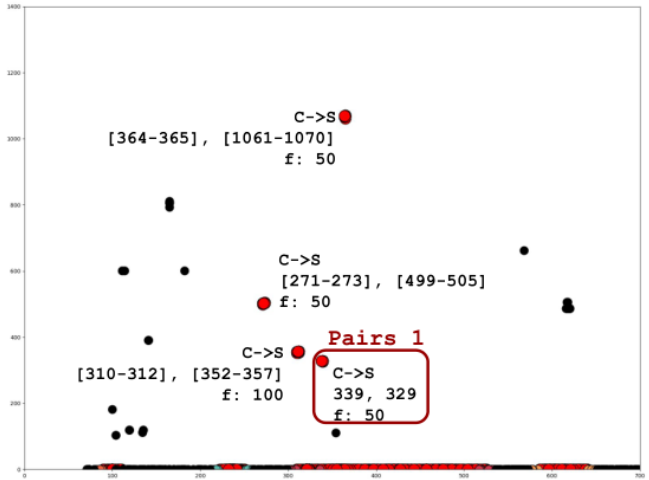
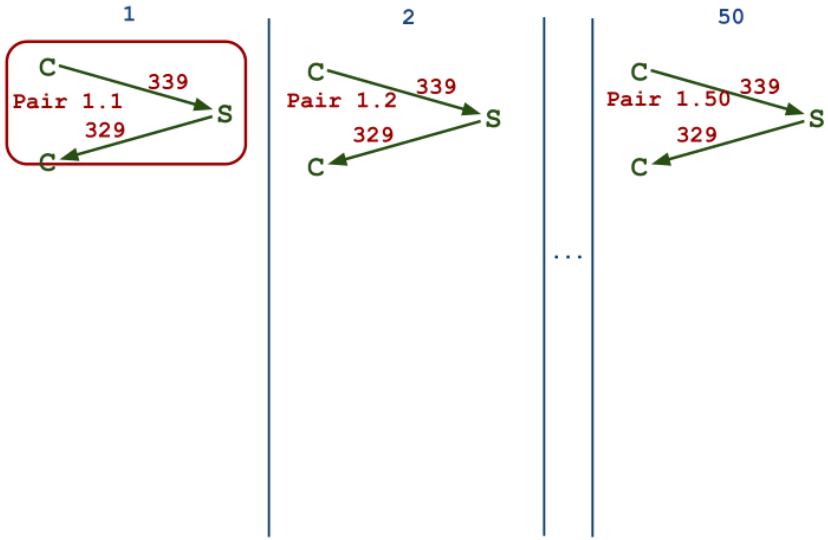
PingPong Training



(b) Arlo Camera



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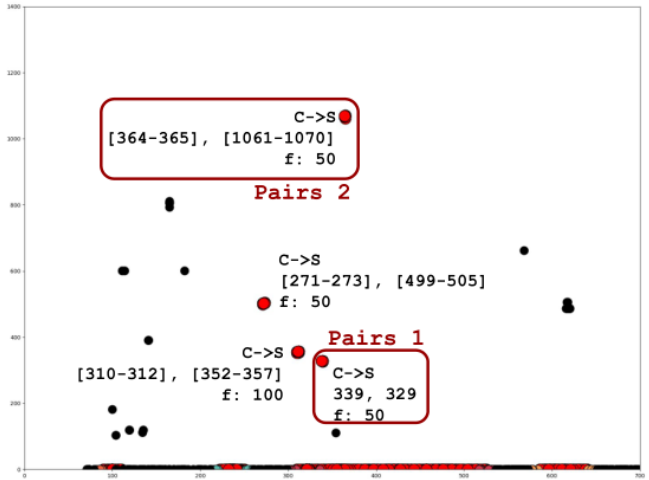
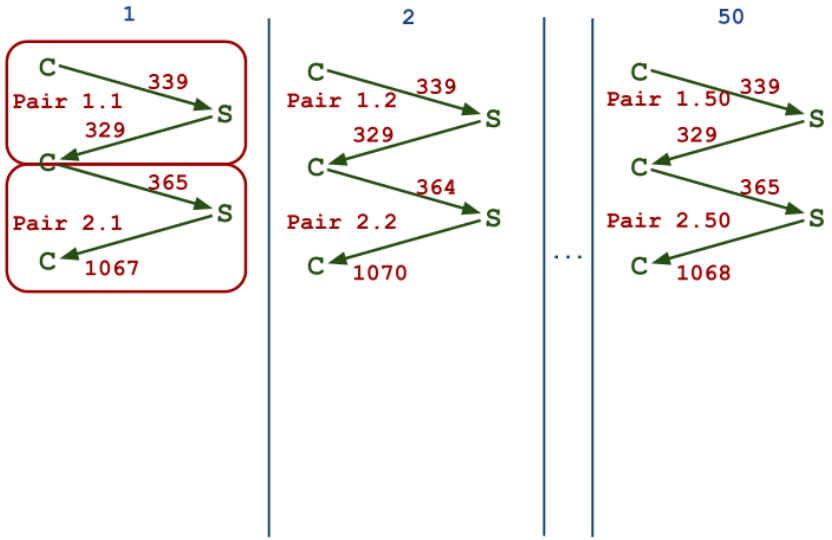
PingPong Training



(b) Arlo Camera



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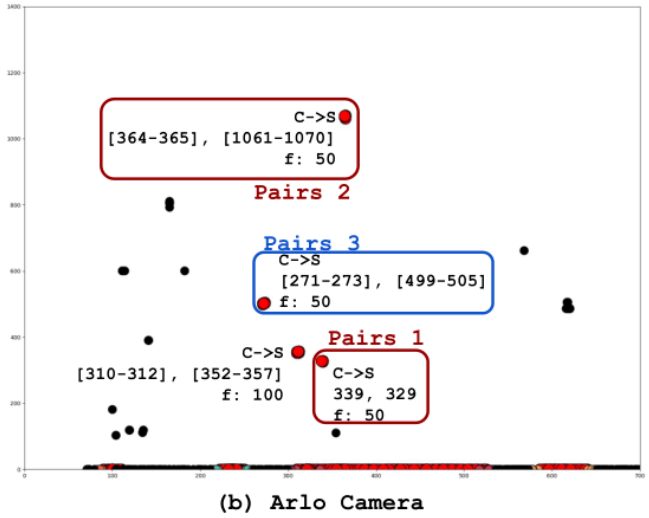
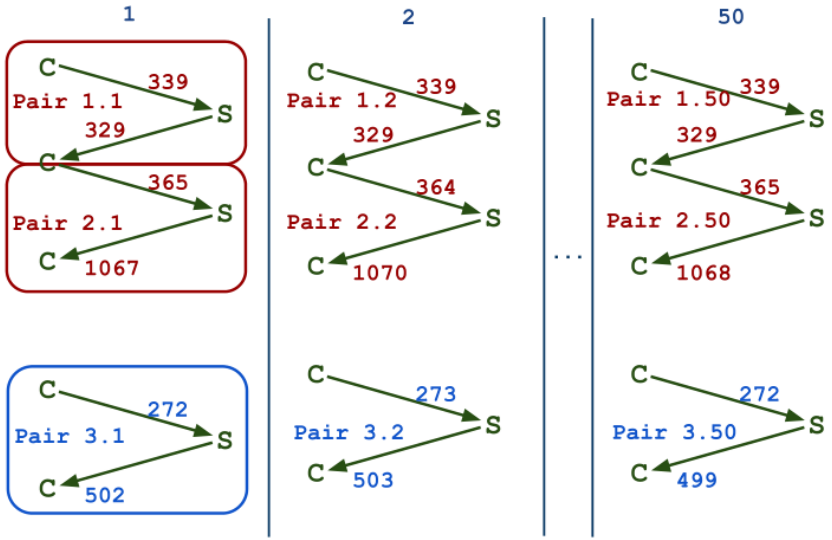
PingPong Training



(b) Arlo Camera



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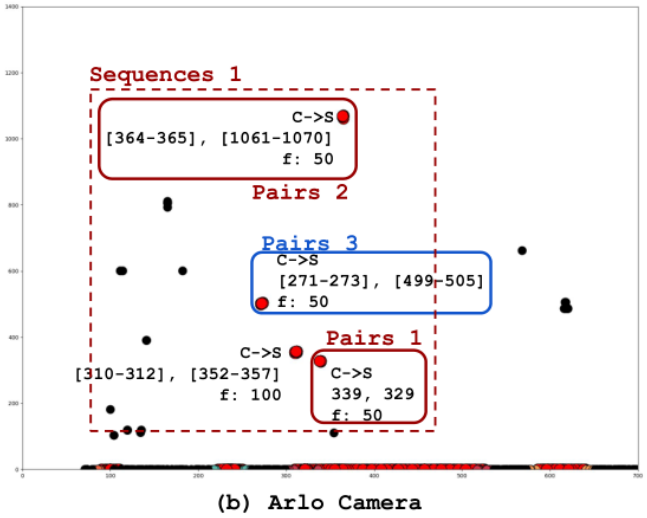
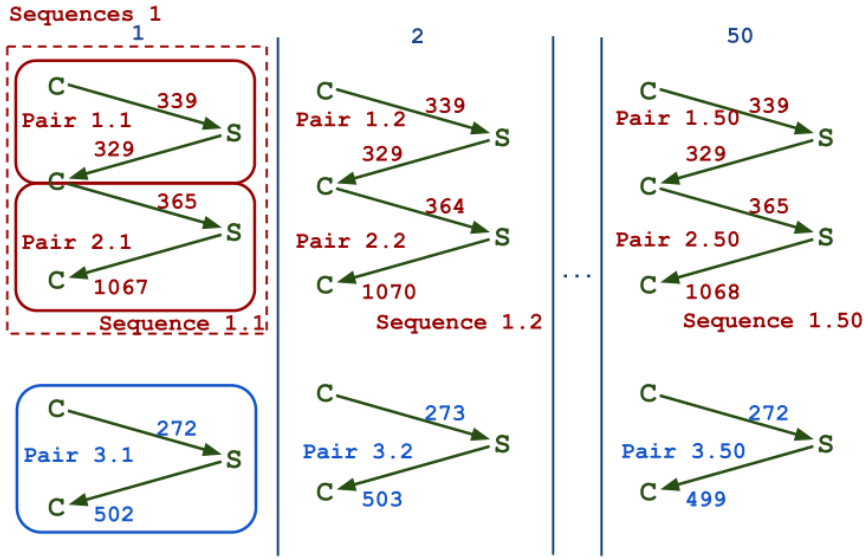
PingPong Training



(b) Arlo Camera



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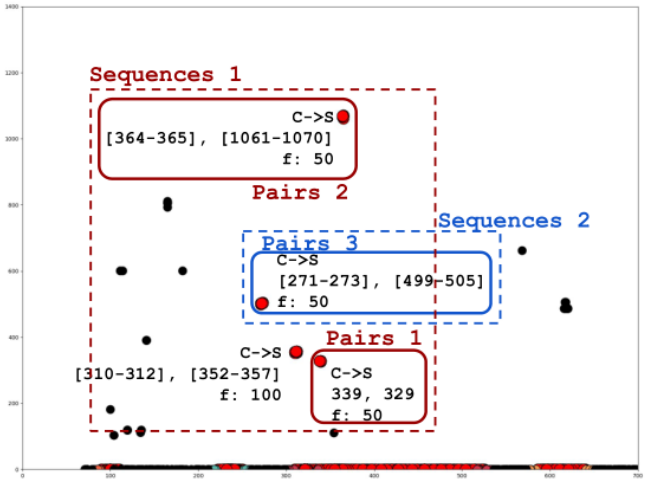
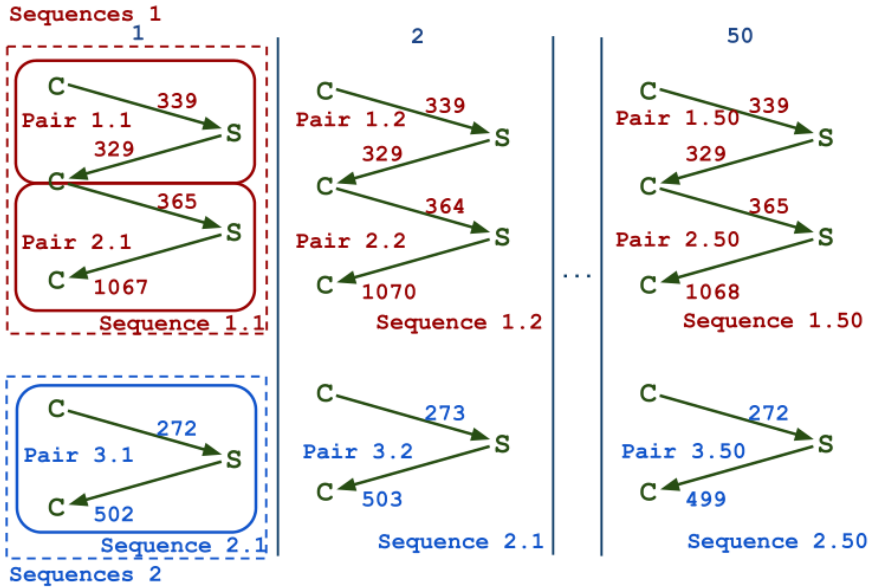
PingPong Training



(b) Arlo Camera



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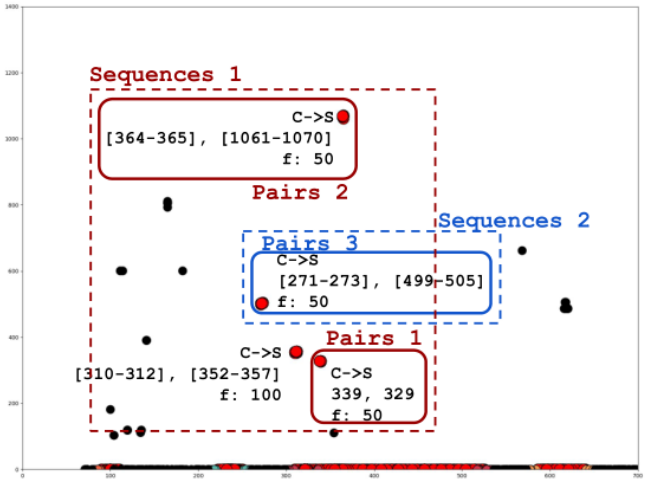
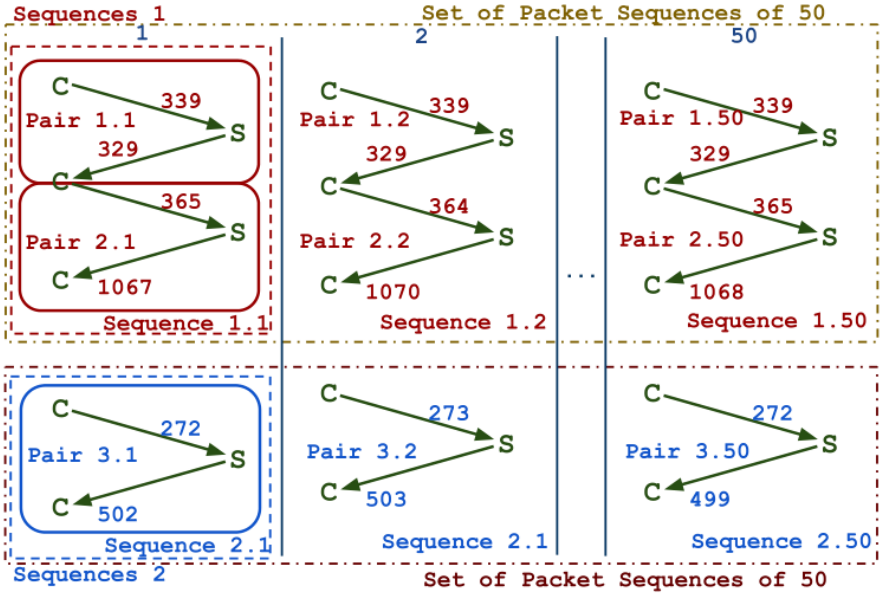
PingPong Training



(b) Arlo Camera



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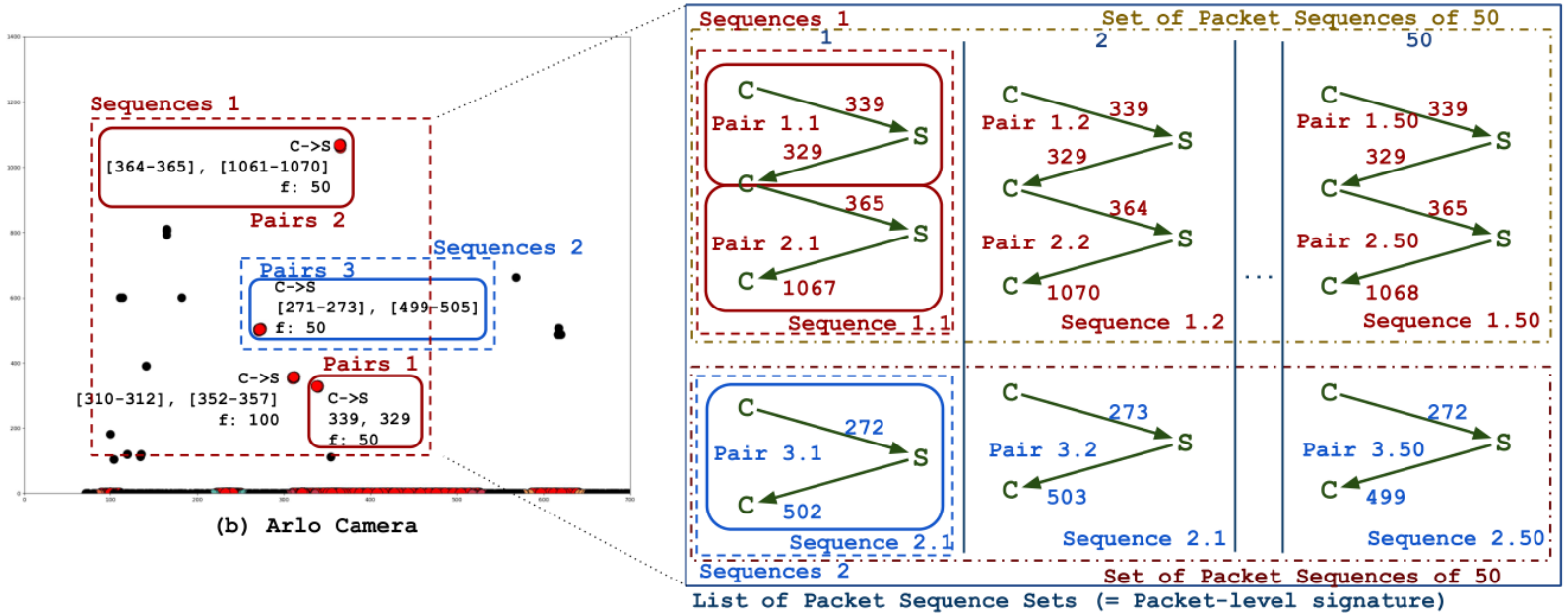
PingPong Training



C-339 S-329 C-[364-365] S-[1061-1070]

C-[271-273] S-[499-505]

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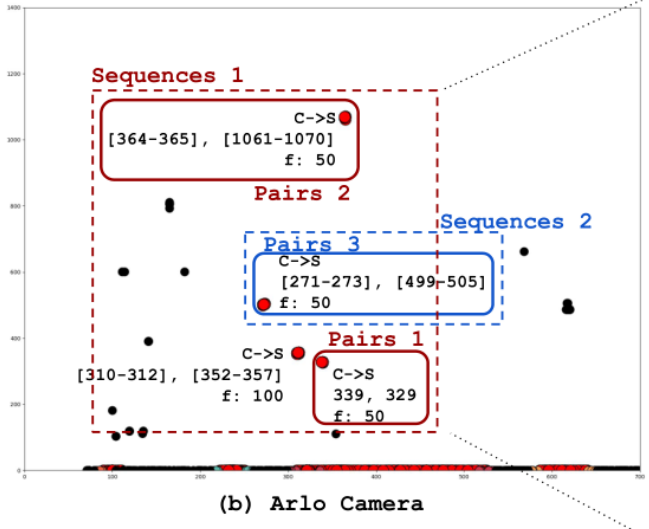
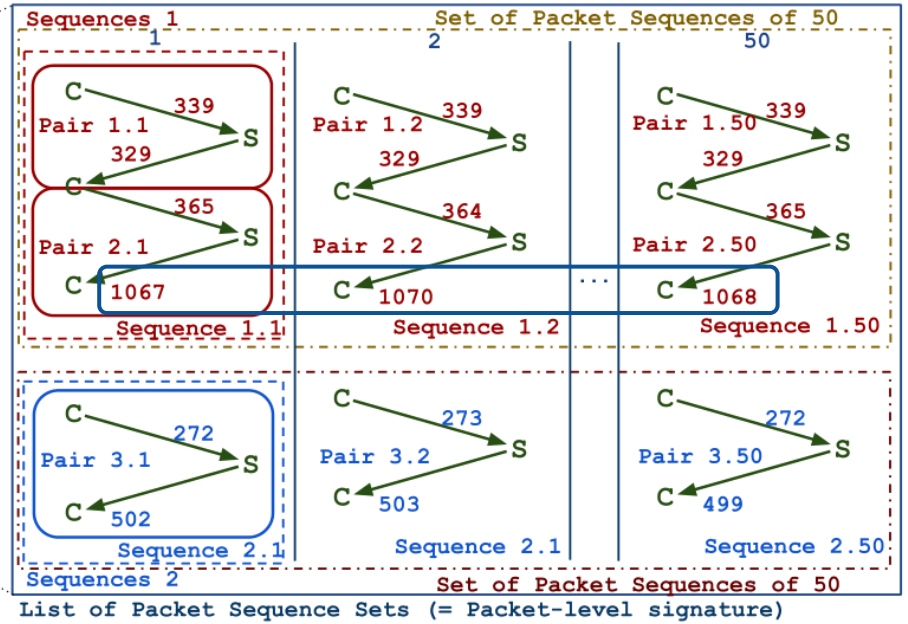
PingPong Training



(b) Arlo Camera



C-339 S-329 C-[364-365] S-[1061-1070]

C-[271-273] S-[499-505]

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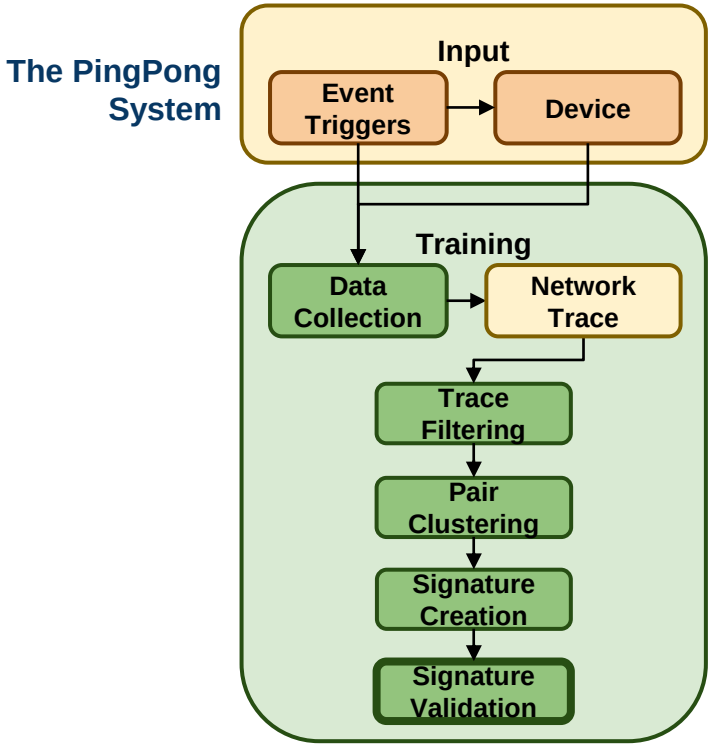
PingPong Training



- Run detection
  - Same PCAP file
- Valid signature iff
  - **n** detected events
  - **n** triggered events
  - **Matching** timestamps

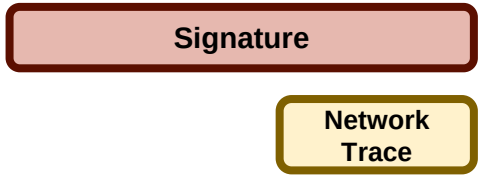
PingPong Detection

Signature

Arlo Camera

C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

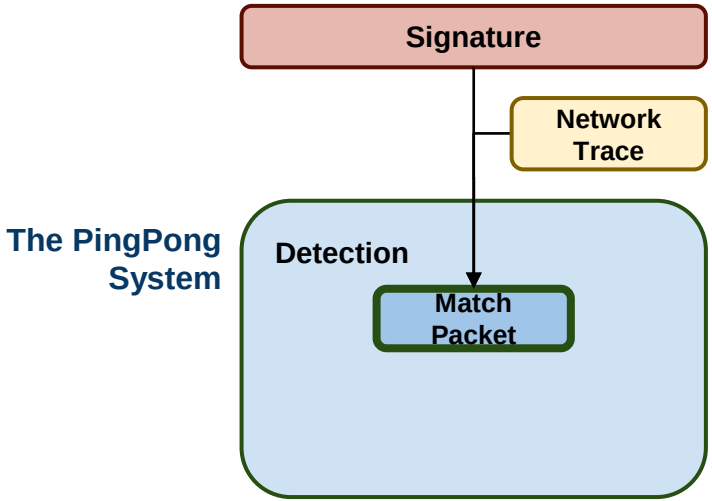
PingPong Detection




```
C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

...
```

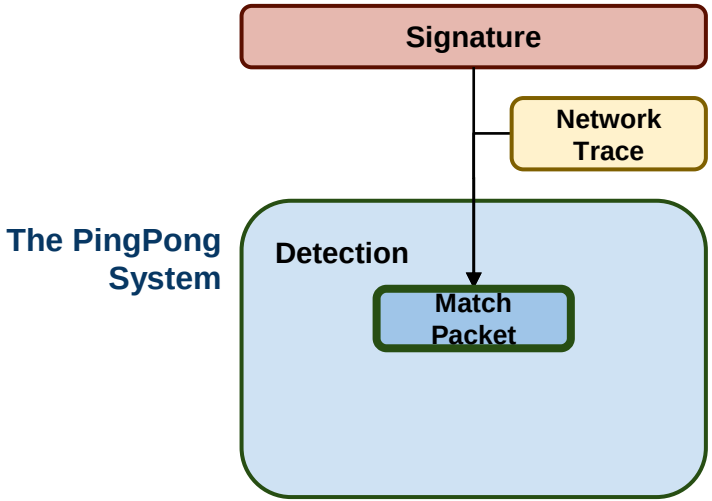
PingPong Detection



C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

... C-339

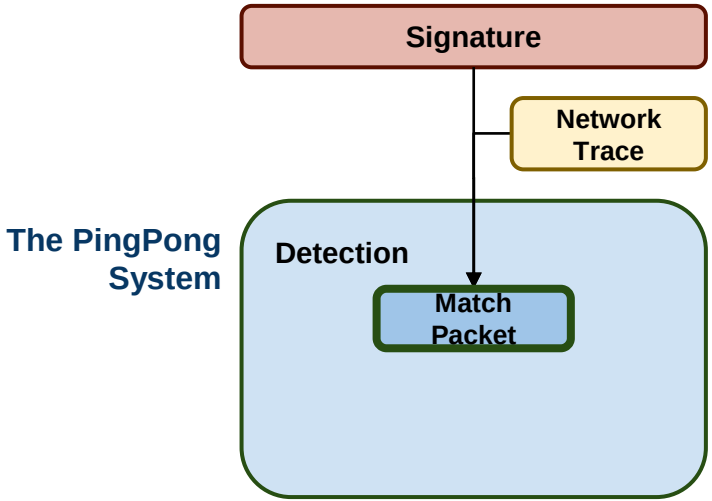
PingPong Detection




```
C-339 S-329 C-[364-365] S-[1061-1070]
      C-[271-273] S-[499-505]

... C-339 S-329
```

PingPong Detection

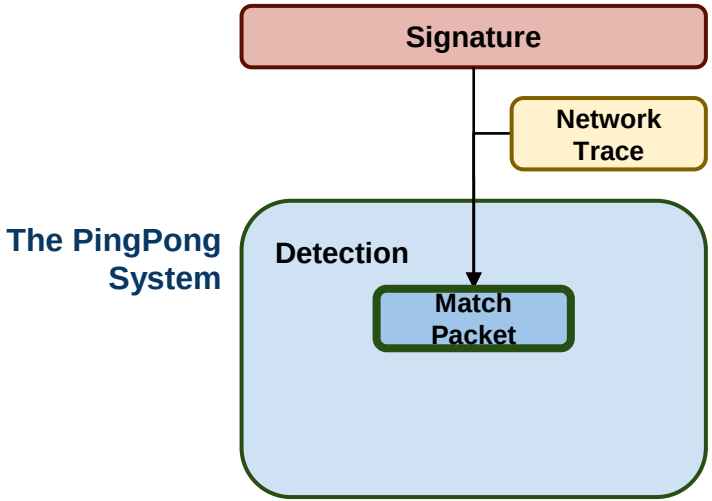


Range-based Matching

```
C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

... C-339 S-329 C-365
```

PingPong Detection



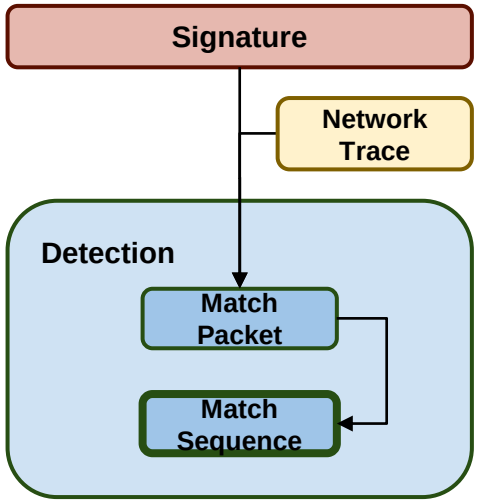
Range-based Matching

C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

... C-339 S-329 C-365 S-1065

PingPong Detection

The PingPong System



First Sequence Matched

```
C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]
```

```
... C-339 S-329 C-365 S-1065
```

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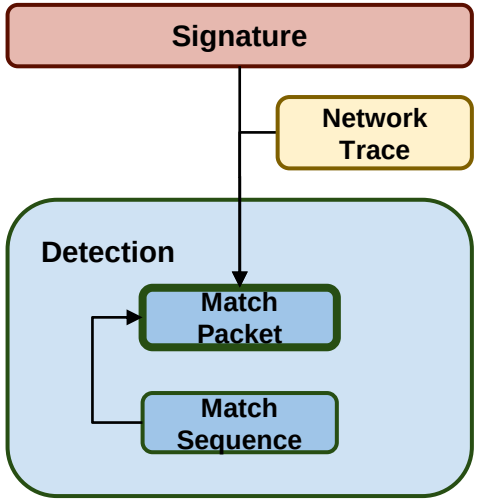
PingPong Detection



The PingPong System

Range-based Matching

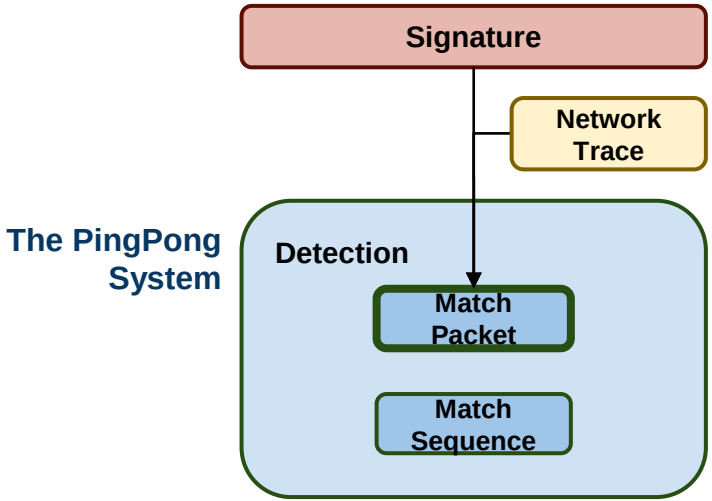
C-339 S-329 C-[364-365] S-[1061-1070]

C-[271-273] S-[499-505]

... C-339 S-329 C-365 S-1065

... C-272

PingPong Detection

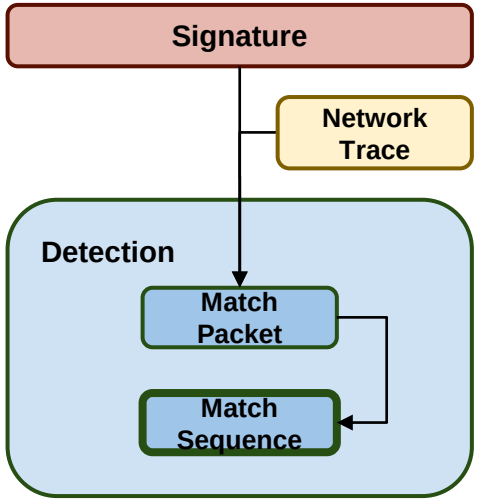


Range-based Matching

```
C-339 S-329 C-[364-365] S-[1061-1070]
      C-[271-273] S-[499-505]

... C-339 S-329 C-365 S-1065
    ... C-272 S-500
```

PingPong Detection



The PingPong System

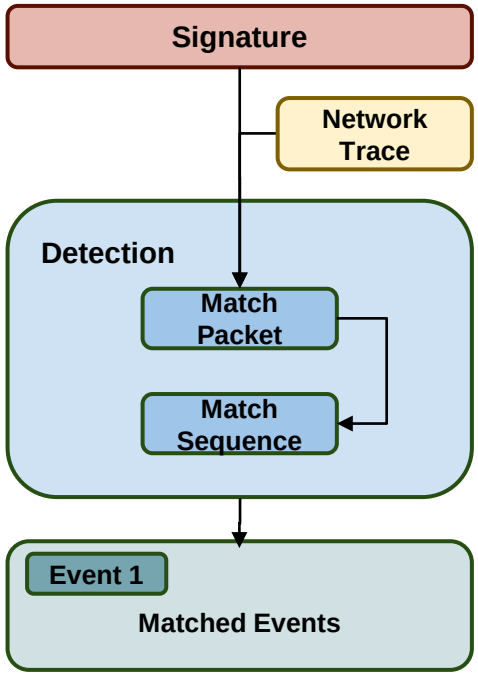
Second Sequence Matched

C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]

... C-339 S-329 C-365 S-1065
... C-272 S-500

PingPong Detection

The PingPong System



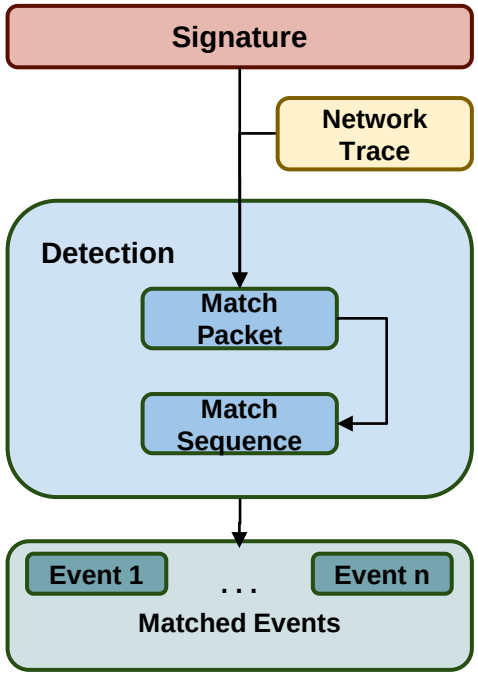
Event Match

```
C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]
```

```
... C-339 S-329 C-365 S-1065
... C-272 S-500
```

PingPong Detection

The PingPong System

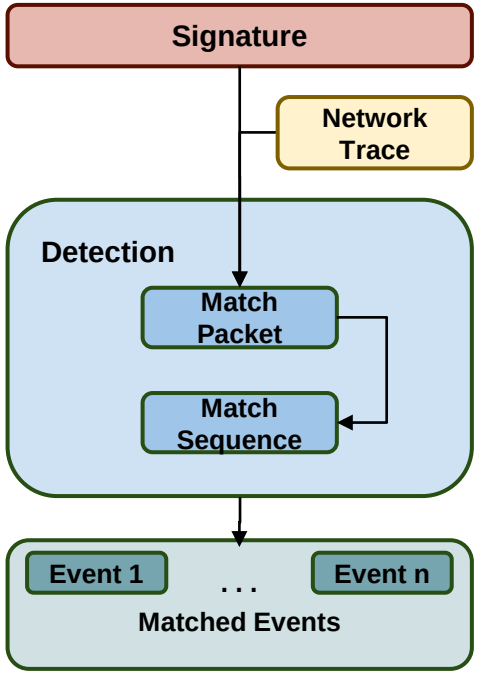


Event Match

```
C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]
```

```
... C-339 S-329 C-365 S-1065
... C-272 S-500
```

PingPong Detection



Event Match

```
C-339 S-329 C-[364-365] S-[1061-1070]
C-[271-273] S-[499-505]
```

```
... C-339 S-329 C-365 S-1065
... C-272 S-500
```

See paper for more detail

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Possible Defenses

- Seemingly not effective defense
  - VPN
  - Traffic injection and shaping

Possible Defenses

- Seemingly not effective defense
  - VPN
  - Traffic injection and shaping
- More effective defense
  - Packet padding
    - Obfuscate packet lengths

Possible Defenses

- Not too effective defense
  - VPN
  - Traffic injection and shaping
- More effective defense
  - Packet padding
    - Obfuscate packet lengths
- **See paper** for detail