StateDiver: Testing Deep Packet Inspection Systems with State-Discrepancy Guidance

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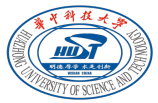

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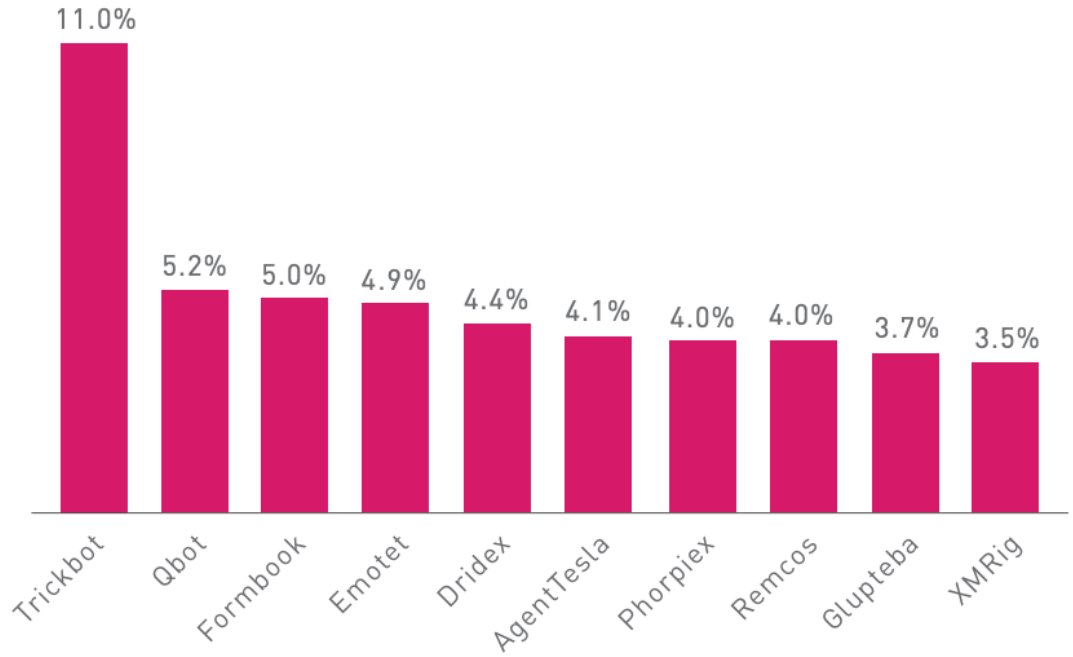
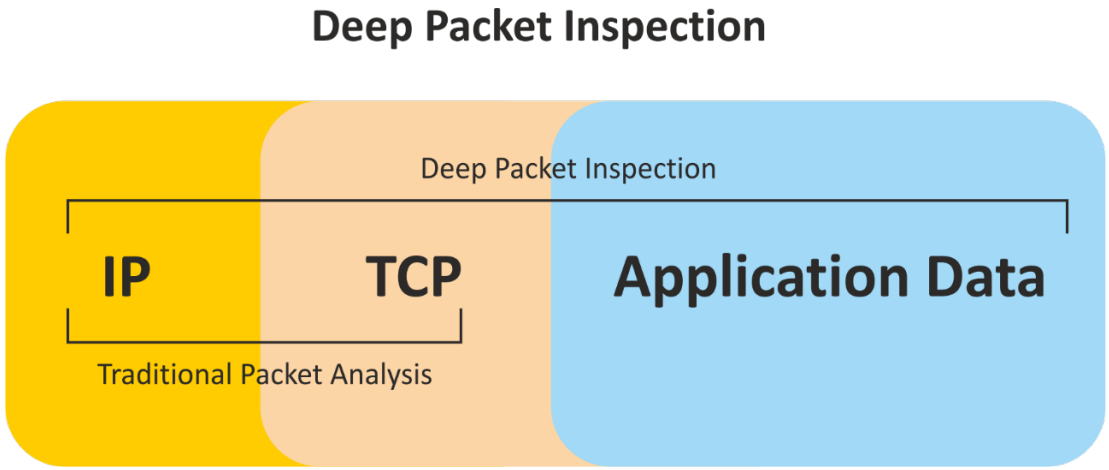
Global Malware Statistics



CheckPoint Research. Percentage of Corporate Networks Attacked by Each Malware Family. Cyber Security Report 2022. 2022



Catchpoint. A Guide to Deep Packet Inspection. 2017

State-of-the-art Solutions

- Manual construction, Symbolic execution and Fuzzing

  INTANG [IMC'17] lib·erate [IMC'17]

  SymTCP [NDSS'20] DPIFuzz [ACSAC'20]

  Geneva [CCS'19] Themis [CCS'21] TCPFuzz [ATC'21]

- Former packets have **rendered** the DPI to an **abnormal** state
  - discrepancy — directly guide fuzzing process
  - no existing work

Our work: StateDiver

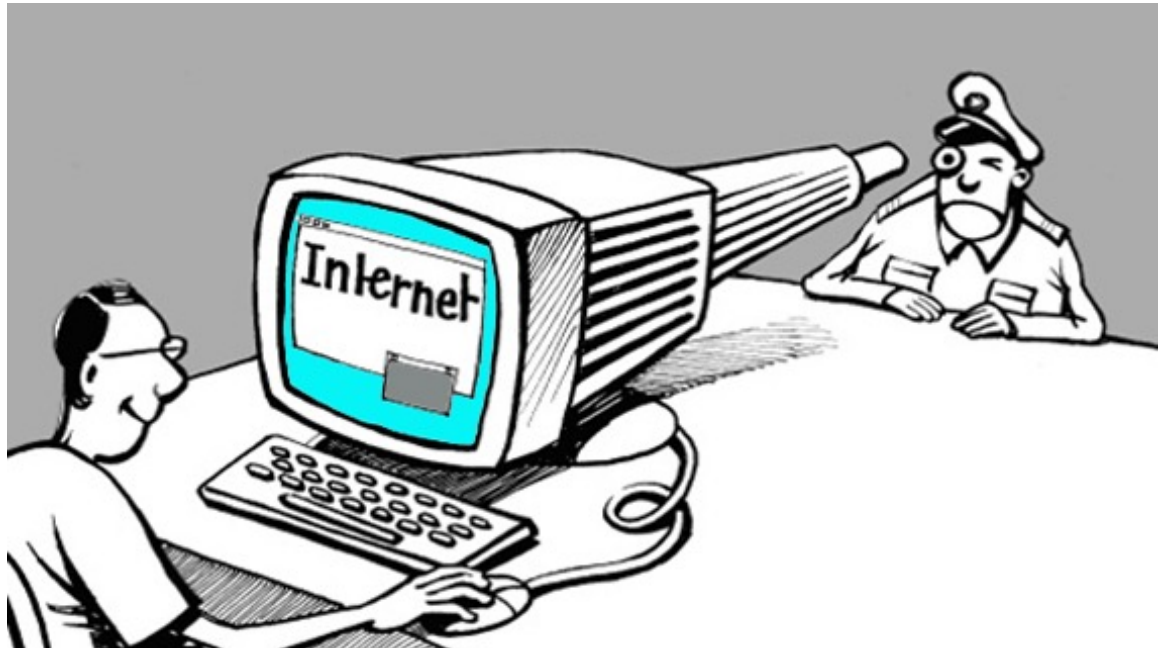
- A fuzzing framework that automatically discovers DPI-bypass strategies using state-discrepancies

- Contributions
  - new feedback mechanism
  - end-to-end system
  - evaluated against 3 most famous open-source DPI systems, and found 16 bypass strategies (8 new and 8 previously known)

Deep Packet Inspection System (DPI)

- Powerful data-processing technique
  - conventional packet filtering (e.g. iptables) : at or below transport layer
  - DPI : application layer or even encrypted data

- Customized protocol stacks
  - track the state of each connection
  - rebuild data streams

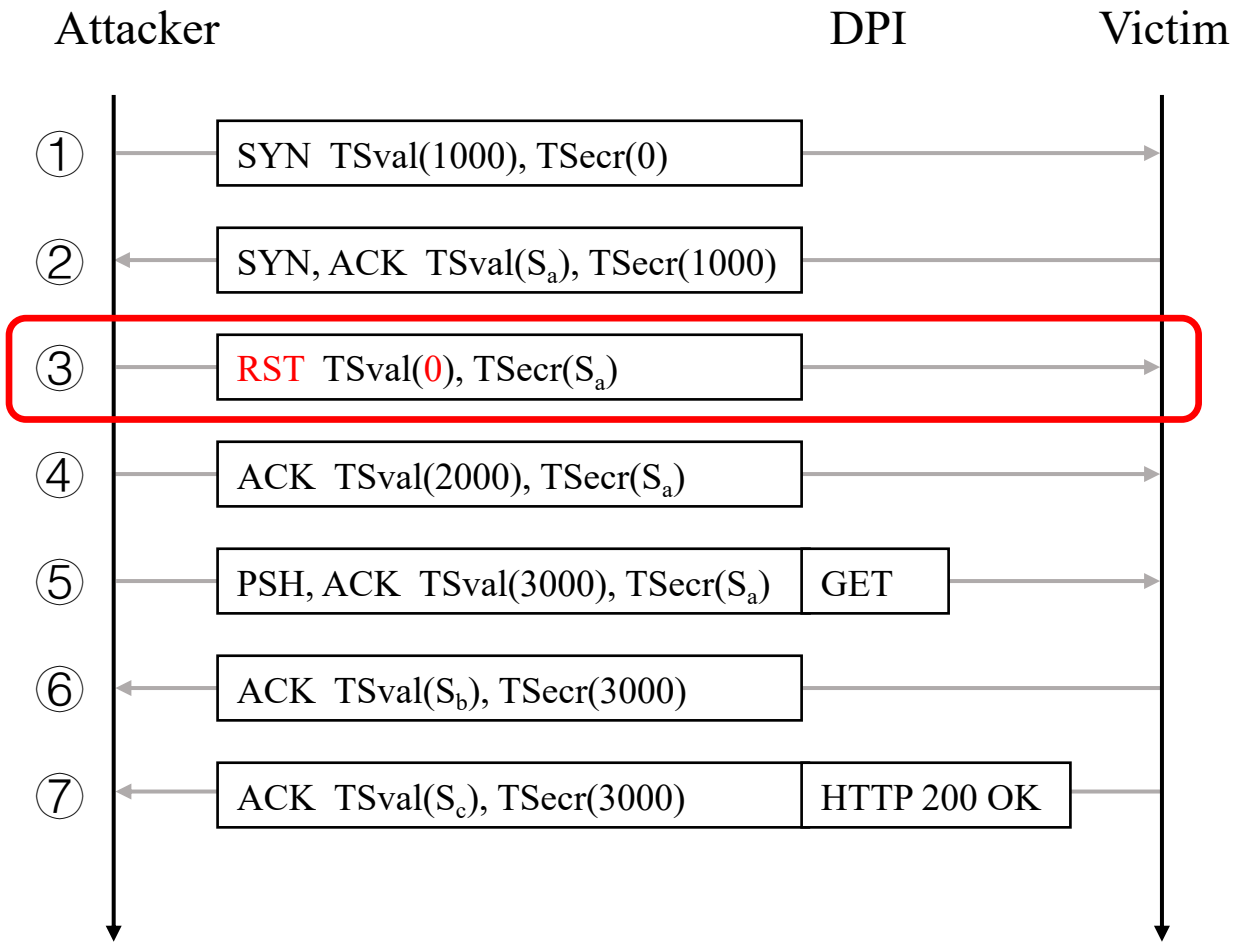


Customized Protocol Stacks

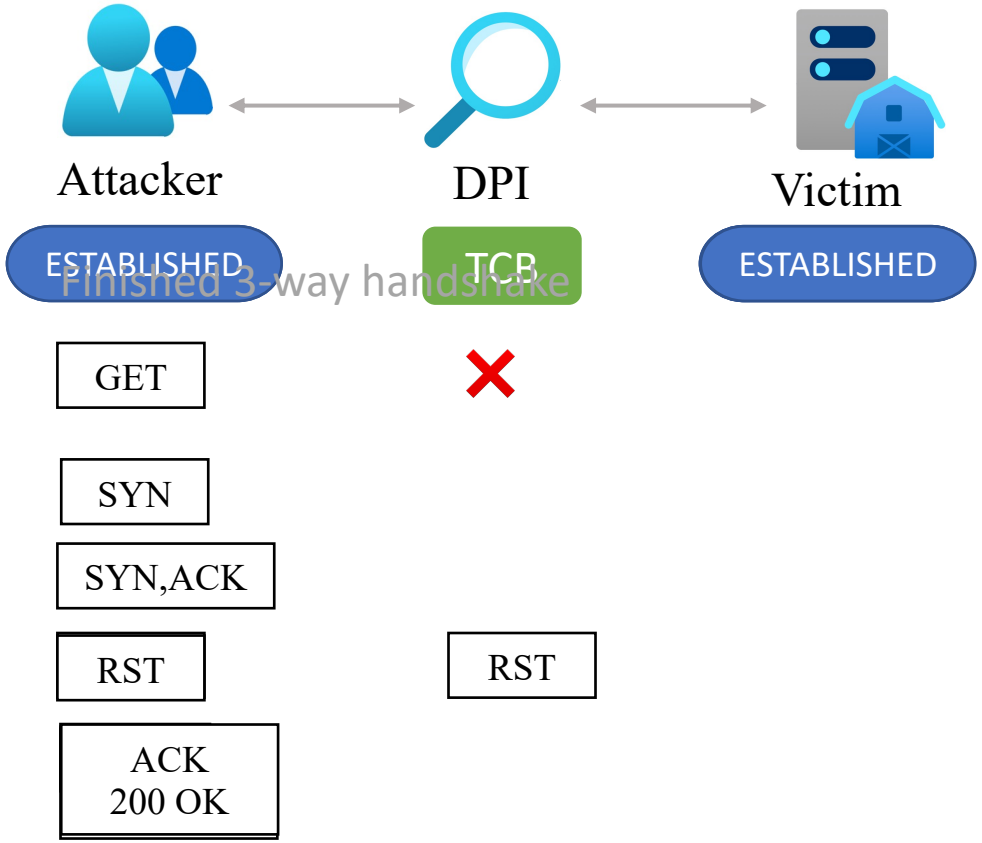
- Reasons
  - generality requirement
  - high throughput requirement
- Risks
  - ambiguous details in RFC files — vulnerable implementation
  - simplified protocol stacks — ignore complicated checks

Different Processing logic  Bypass Attacks

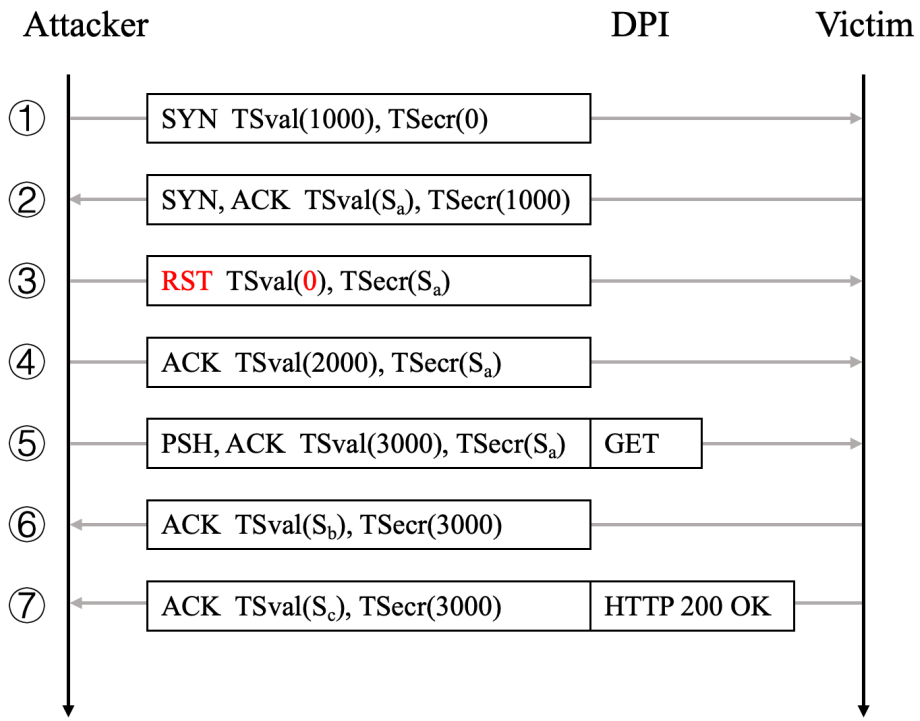
Bypass Attack Example



TCP Timestamps Option:
TSval: Timestamp Value
TSecr: Timestamp Echo Reply
PAWS Checking: TSval < last one -> ignore



Motivation Example



No.	Packet	Direction	Buggy DPI	Normal DPI
①	SYN TSval(1000) TSecr(0)	To Server	Sn_c: SYN_SENT Sn_s: LISTEN	Su_{st}: SYN_SENT
②	SYN, ACK TSval(S_a) TSecr(1000)	To Client	Sn_c: SYN_SENT Sn_s: LISTEN⇒SYN_RCVD	Su_{st}: SYN_SENT⇒SYN_RCVD
③	RST TSval(0) TSecr(S_a)	To Server	Sn_c: SYN_SENT⇒CLOSED Sn_s: SYN_RCVD	
④	ACK TSval(2000) TSecr(S_a)	To Server		Su_{st}: SYN_RCVD⇒ESTABLISHED
⑤	GET TSval(3000) TSecr(S_a)	To Server		
⑥	ACK TSval(S_b) TSecr(3000)	To Client		
⑦	HTTP 200 OK TSval(S_c) TSecr(3000)	To Client		

Identify and prioritize these packets/packet sequences

Challenge 1: Identify Abnormal State

1. Without a deep understanding of the DPI system
2. Without the protocol details

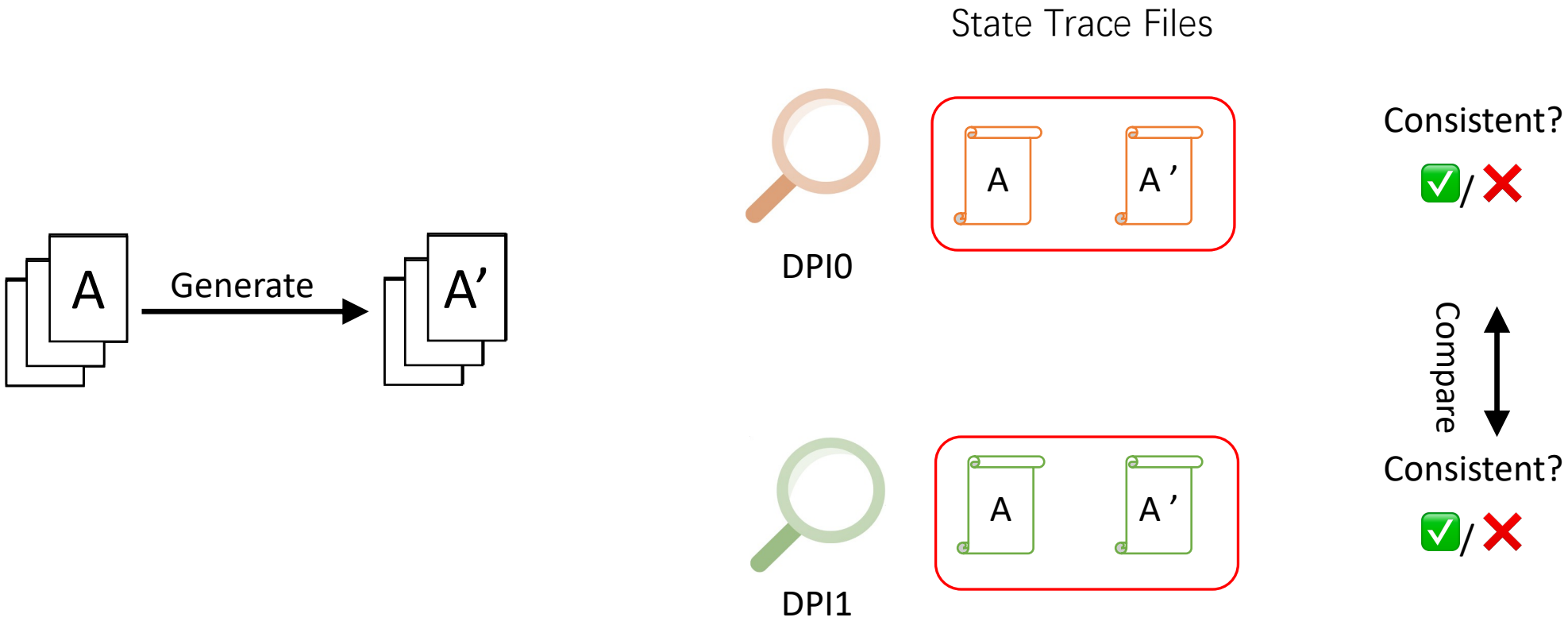
Solutions: monitor **multiple** DPI systems

- just one input ❌
- just one DPI system ❌

one pair of inputs ✅

multiple DPI systems ✅

Differential Analysis Algorithm



Differential Analysis Algorithm

Algorithm 1 Differential Analysis

```
1: DPI0StatAlt ← CmpDPI(parDPI0Stat, currDPI0Stat)
2: DPI1StatAlt ← CmpDPI(parDPI1Stat, currDPI1Stat)
3: if DPI0StatAlt is True xor DPI1StatAlt is True then
4:     evaluation ← best_score
5: else if DPI0StatAlt is True and DPI1StatAlt is True then
6:     evaluation ← good_score
7: else if DPI0StatAlt is False and DPI1StatAlt is False then
8:     evaluation ← moderate_score
9: end if
10: return evaluation
```

Challenge 2: State Extract

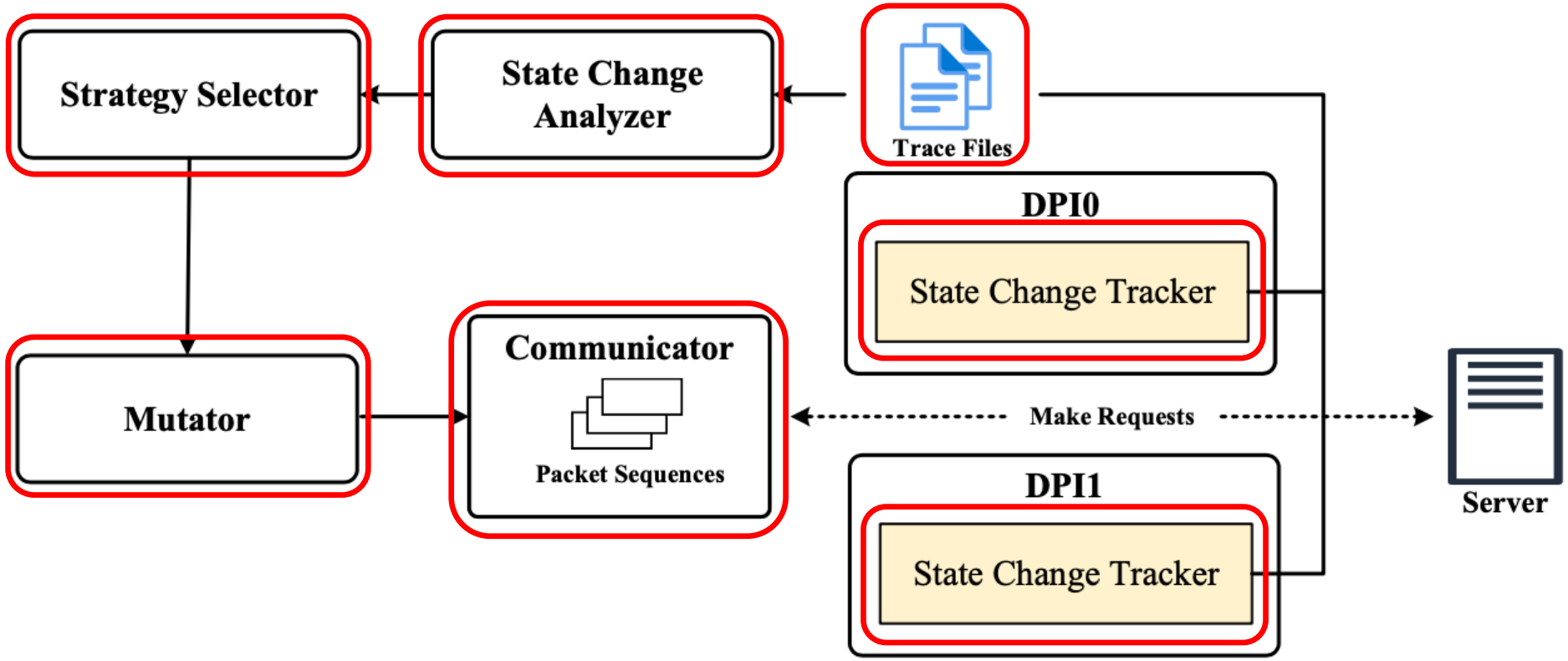
- State Instrumentation
  - Debug option
  - State processing functions

    e.g. accept/drop/return point

```
/* this env var uses the lower 32 bits of the flags: */
#define DEBUG_VARIABLE "SNORT_DEBUG"

#define DEBUG_INIT            0x0000000000000001LL
#define DEBUG_PARSER          0x0000000000000002LL
#define DEBUG_MSTRING         0x0000000000000004LL
#define DEBUG_PORTLISTS       0x0000000000000008LL
#define DEBUG_ATTRIBUTE       0x0000000000000010LL
#define DEBUG_PLUGIN          0x0000000000000020LL
#define DEBUG_PLUGBASE        0x0000000000000040LL
#define DEBUG_DECODE          0x0000000000000080LL
#define DEBUG_DATALINK        0x0000000000000100LL
#define DEBUG_CONFIGRULES     0x0000000000000200LL
#define DEBUG_RULES           0x0000000000000400LL
#define DEBUG_DETECT          0x0000000000000800LL
#define DEBUG_PATTERN_MATCH   0x0000000000001000LL
#define DEBUG_FLOW            0x0000000000002000LL
#define DEBUG_LOG             0x0000000000004000LL
#define DEBUG_FLOWBITS        0x0000000000008000LL
#define DEBUG_FILE            0x0000000000010000LL
#define DEBUG_CONTROL         0x0000000000020000LL
#define DEBUG_EXP             0x0000000080000000LL
```

StateDiver Architecture



Evaluation

- Q1: Bypasses found against real-world DPIs
- Q2: Efficacy of state-discrepancy guidance
- Q3: Performance compared with state-of-the-art evasion works

Table 4: Bypass Identified by StateDiver

Strategy Name	Illustration	Affected DPI		
		Snort	Snort++	Suricata
△ RST bad Timestamp	Send RST with invalid TCP timestamp option	✓	✓	✓
△ RST/ACK bad Timestamp	Send RST/ACK with invalid TCP timestamp option	✓	✓	✓
△ RST bad MD5	Send RST with invalid TCP MD5 option	✓	✓	
△ RST/ACK bad MD5	Send RST/ACK with invalid TCP MD5 option	✓	✓	
△ Timestamp gap	Send partial request with TCP timestamp option, then send the remaining request with TCP timestamp = last_timestamp + long gap (2147483648)	✓		
△ RST/ACK bad ACK number	Send RST with corrupted ACK number in ESTABLISHED state	✓	✓	
△ Multiple SYNs	Send another SYN with corrupted SEQ number in 3-way handshake		✓	
△ TCB Turnaround	Send SYN/ACK before sending the SYN packet		✓	
★ FIN with data	Send FIN with junk data in ESTABLISHED state, then send the request in TCP segments	✓		
★ SYN bad MD5	Send SYN with invalid TCP MD5 option in ESTABLISHED state, then send the request	✓	✓	
★ SYN Fragment	Send junk data in ESTABLISHED state, then send SYN with junk data, finally send the request	✓		
★ Fragment and Segment	Combination of multiple IP fragmentations and TCP segmentations	✓		
★ FIN bad ACK number	In SYN_RECV state, send FIN and ACK with same corrupted ACK number successively, then send the request		✓	
★ ACK bad ACK number and data with smaller Timestamp	Send ACK with corrupted ACK number in ESTABLISHED state, then send request with TCP timestamp = last_timestamp - gap (10)		✓	
★ ACK bad MD5 and data with smaller Timestamp	Send ACK with invalid TCP MD5 option in ESTABLISHED state, then send request with TCP timestamp = last_timestamp - gap (10)		✓	
★ PSH before SYN	Send PSH without data before 3-way handshake		✓	

△ means previous known strategies, and ★ means new strategies.

Q2: Contributions of State Discrepancies

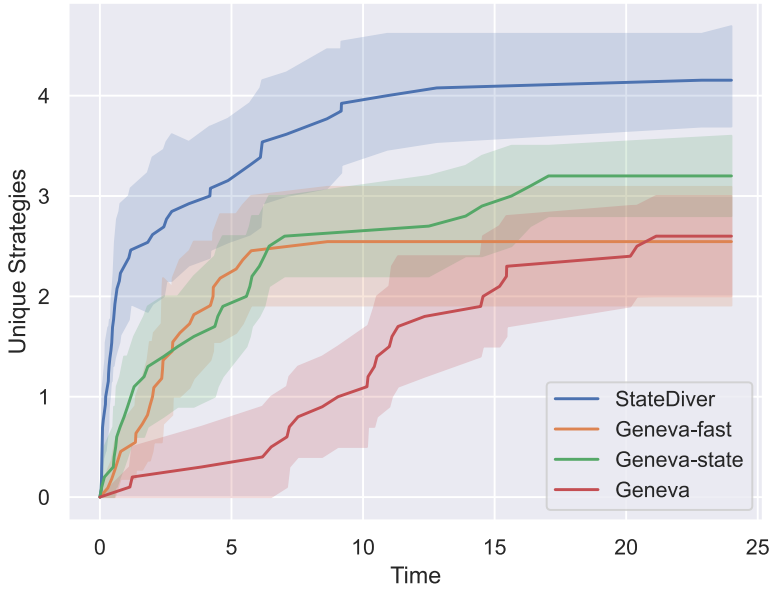
Tools	Illustration
StateDiver	Our tool using state-discrepancies guidance

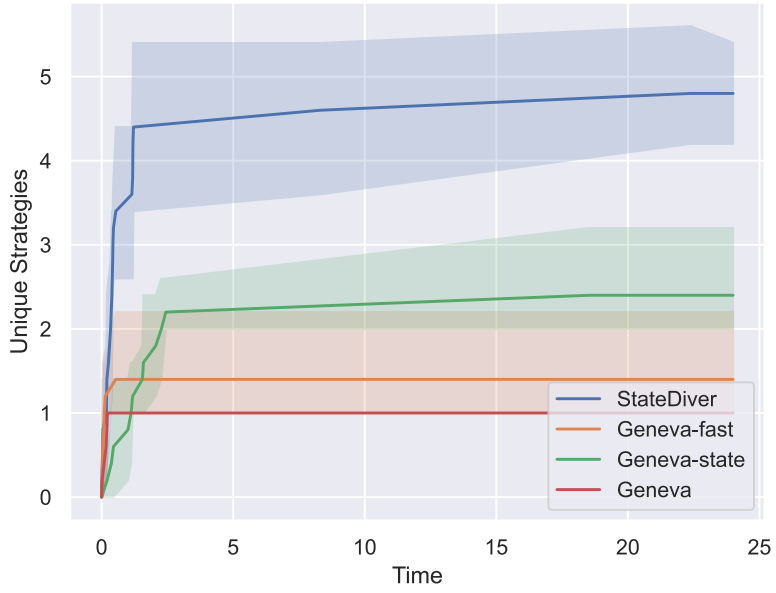
Q2: Contributions of State Discrepancies

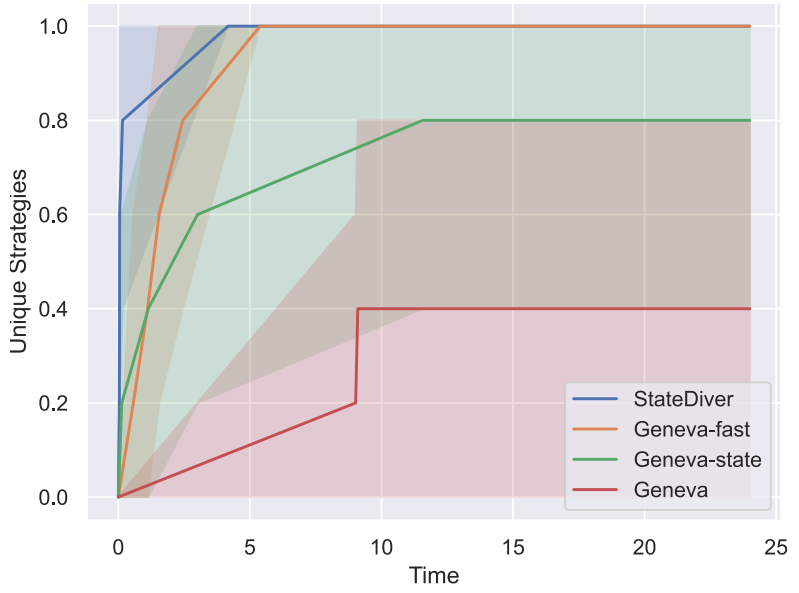
Tools	Illustration
StateDiver	Our tool using state-discrepancies guidance
Geneva (CCS'19)	Perform fuzzing on DPI leveraging server-side responses
Geneva-fast [added]	Geneva + local test enhancement
Geneva-state [added]	Geneva + state-discrepancies guidance

Run each tool 5 times, each time lasts 24h, on 3 DPI systems.

Q2: (1)(2) Unique Bypasses & Speed







Unique bypasses founded by evaluated fuzzers for 24h in Snort , Snort++, and Suricata respectively

Q2: (3) Unique State Transitions

LISTEN
SYN_SENT
SYN_RECV
ESTABLISHED
FIN_WAIT_1
CLOSE_WAIT
FIN_WAIT_2
LAST_ACK
TIME_WAIT
CLOSED
CLOSING

Target DPI	Variables	GENEVA	GENEVA-*state*	GENEVA-*fast*	STATEDIVER
Snort	Sn_c	15.8	19.8	25.0	29.4
	Sn_s	22.0	24.4	28.6	32.2
Snort++	Sp_c	12.6	20.4	15.8	25.4
	Sp_s	20.8	25.4	27.2	31.4
Suricata	Su_{st}	13.6	18.8	26.4	34.0

Q3: Comparison with State-of-the-art Tools

- State-of-the-art tools

  INTANG [IMC'17] lib·erate [IMC'17]

  Geneva [CCS'19] SymTCP [NDSS'20] Themis [CCS'21]

- Use attack dataset in Themis

  all the TCP-related evasion strategies in former works

Table 6: Prior Work's TCP-based Strategies and StateDiver Found on Suricata

Strategy Name	*INTANG*	*lib·erate*	*Geneva*	*SymTCP*	*Themis*	StateDiver
△ RST_Bad_MD5	✓		✓	✓	✓	✓
△ RST/ACK_Bad_MD5	✓		✓	✓	✓	✓
△ SEQ_Number_Before_ISN					✓	

Table 7: Prior Work's TCP-based Strategies and StateDiver Found on Snort

Strategy Name	*INTANG*	*lib·erate*	*Geneva*	*SymTCP*	*Themis*	StateDiver
△ RST_Bad_Timestamp	✓		✓	✓		✓
△ RST/ACK_Bad_Timestamp	✓		✓	✓		✓
△ In_Window_FIN				✓		
△ RST_Bad_MD5	✓		✓	✓		✓
△ RST/ACK_Bad_MD5	✓		✓	✓		✓
△ Timestamp_Gap				✓		✓
△ Urgent_data				✓		
△ In_Window_RST				✓		
△ MD5_FIN_ACK				✓		
△ MD5_FIN_Bad_ACK				✓		
△ Multiple_SYNs	✓			✓		
△ RST/ACK_Bad_ACK_Number			✓	✓		✓
△ RST_Bad_SEQ				✓		
△ No_ACK_Flag_FIN				✓		
△ RST_After_FIN					✓	
△ SYN+FIN		✓				
★ FIN_With_Data						✓
★ SYN_Bad_MD5						✓
★ SYN_Fragment			✓♯			✓
★ Fragment_And_Segment			✓♯			✓

Table 8: Prior Work's TCP-based Strategies and StateDiver Found on Snort++

Strategy Name	*INTANG*	*lib·erate*	*Geneva*	*SymTCP*	*Themis*	StateDiver
△ RST_Bad_Timestamp	✓		✓	✓		✓
△ RST/ACK_Bad_Timestamp	✓		✓	✓		✓
△ RST_Bad_MD5	✓		✓	✓	✓	✓
△ RST/ACK_Bad_MD5	✓		✓	✓	✓	✓
△ RST/ACK_Bad_ACK_Number			✓♯	✓		✓
△ Timestamp_Gap				✓	✓	
△ In_Window_RST				✓	✓	
△ RST_After_FIN					✓	
△ No_ACK_Flag_FIN				✓	✓	
△ In_Window_SYN					✓	
△ TCB_Turnaround	✓		✓		✓	✓
△ Multiple_SYNs	✓			✓	✓	✓
★ SYN_Bad_MD5						✓
★ FIN_Bad_ACK_Number						✓
★ ACK_Bad_ACK_Number_And_Data_With_Smaller_Timestamp						✓
★ ACK_Bad_MD5_And_Data_With_Smaller_Timestamp						✓
★ PSH_Before_SYN						✓

△ means previous known strategies
★ means new strategies

Conclusion: StateDiver

- End-to-end fuzzing framework uses state discrepancy between DPIs to discover bypass strategies
- Tested on 3 most famous open-source DPIs, and found 16 bypass strategies (8 new and 8 previously known)
- Help developers detect and fix implementation bugs

https://github.com/CGCL-codes/StateDiver

Thanks & Questions

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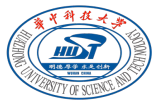

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