ShadowAuth: Backward-Compatible Automatic CAN Authentication for Legacy ECUs

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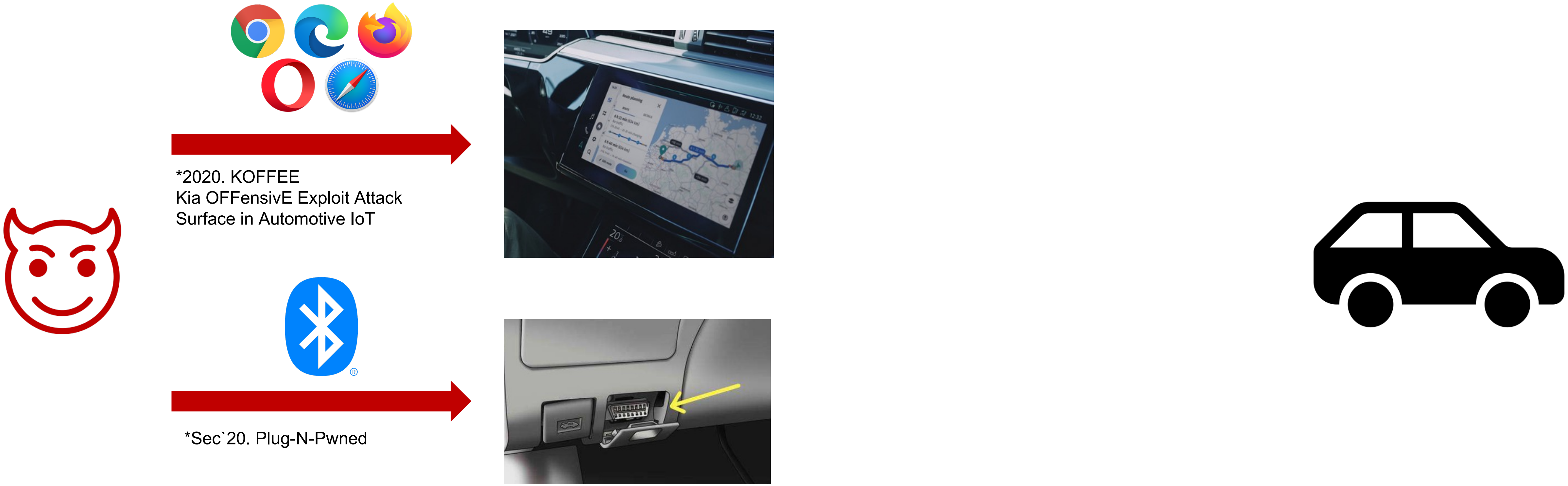
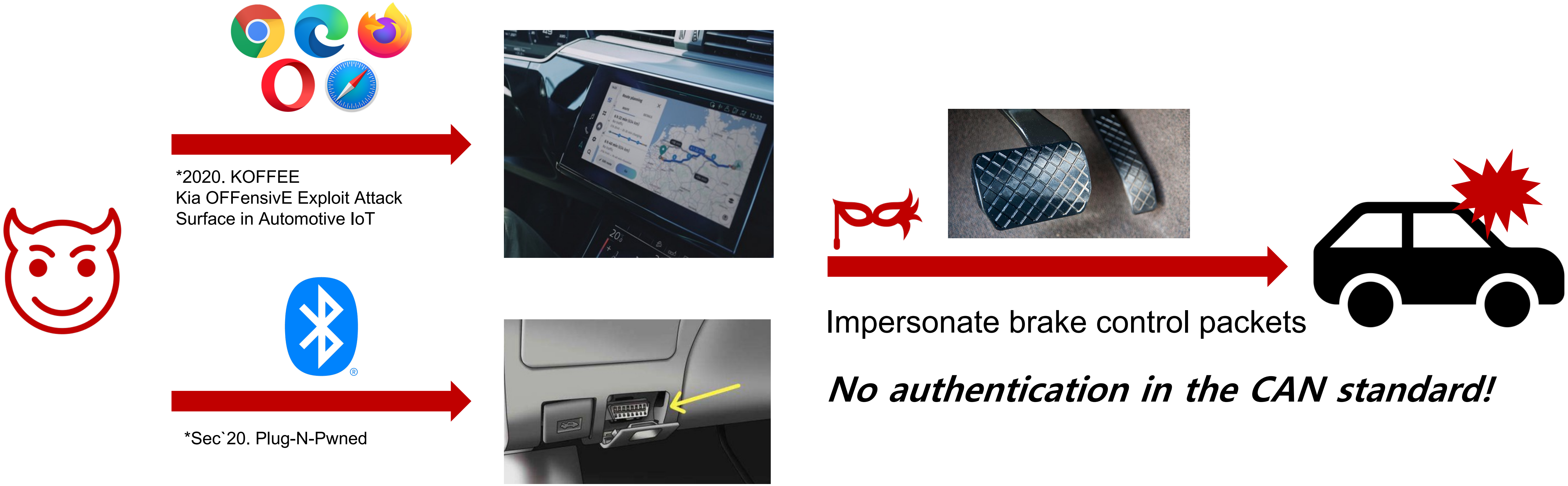
Remote Attacks on In-vehicle Network



*2020. KOFFEE
Kia OFFensivE Exploit Attack
Surface in Automotive IoT

*Sec`20. Plug-N-Pwned

Remote Attacks on In-vehicle Network



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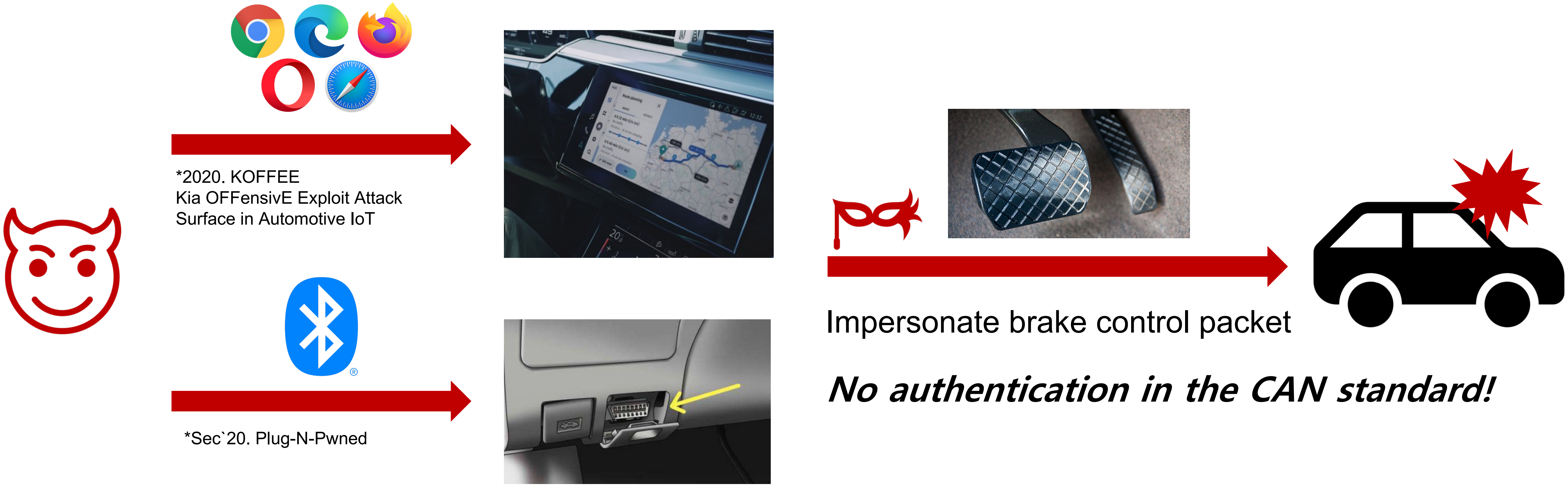
Impersonate brake control packets

No authentication in the CAN standard!

Remote Attacks on In-vehicle Network



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Surface in Automotive IoT

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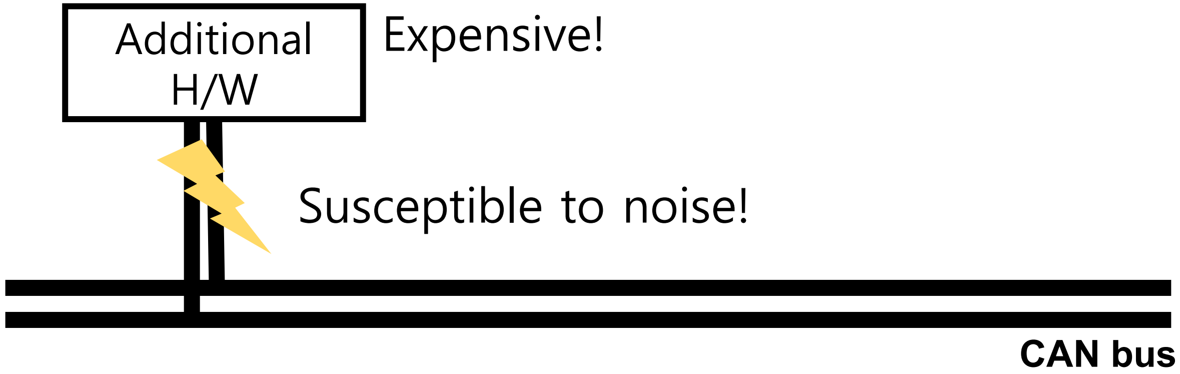
Impersonate brake control packet

No authentication in the CAN standard!

- Previous works proposed authentication feature, but…
- Why has no one **not been deployed** in real-world?

Previous works

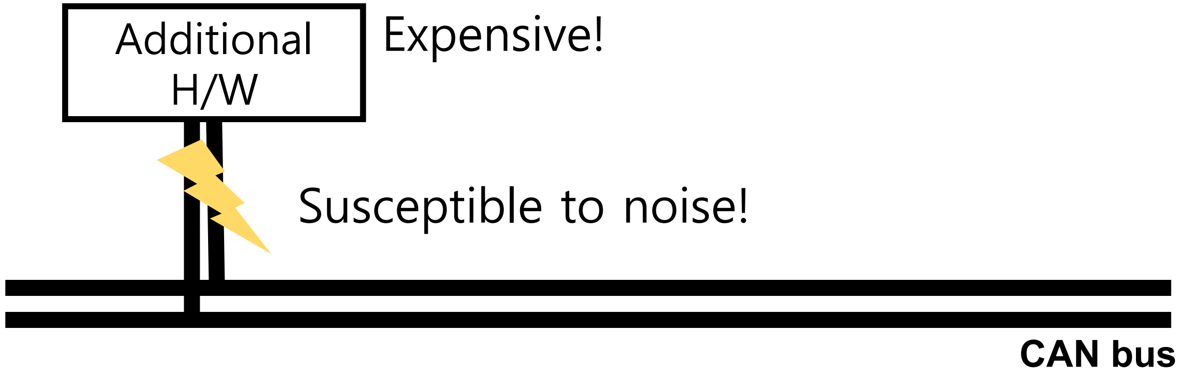
- Side channel-based IDS
  - Additional H/W
  - Not reliable
  - *VIDEN, EASI, CIDS, …



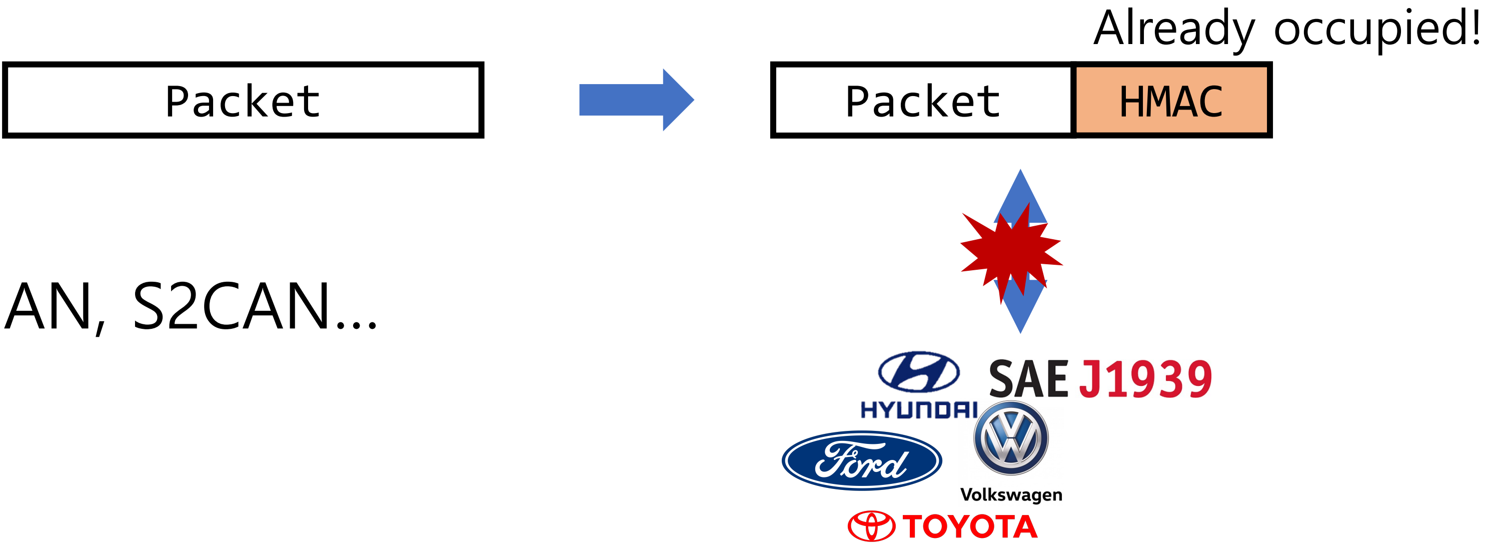
* CCS`17, USENIX`16, NDSS`20

Previous works

- Side channel-based IDS
  - Additional H/W
  - Not reliable
  - VIDEN, EASI, CIDS, …



- HMAC-based IDS
  - Incompatible new packet
  - Additional delay
  - *CANAuth, TOUCAN, LiBRA-CAN, S2CAN…



* ECRYPT`11, AUTOSEC`19, CNS`12, ACSAC `21

Design Goals

- Backward-compatibility
- Accuracy
- No extra delay
- No extra H/W

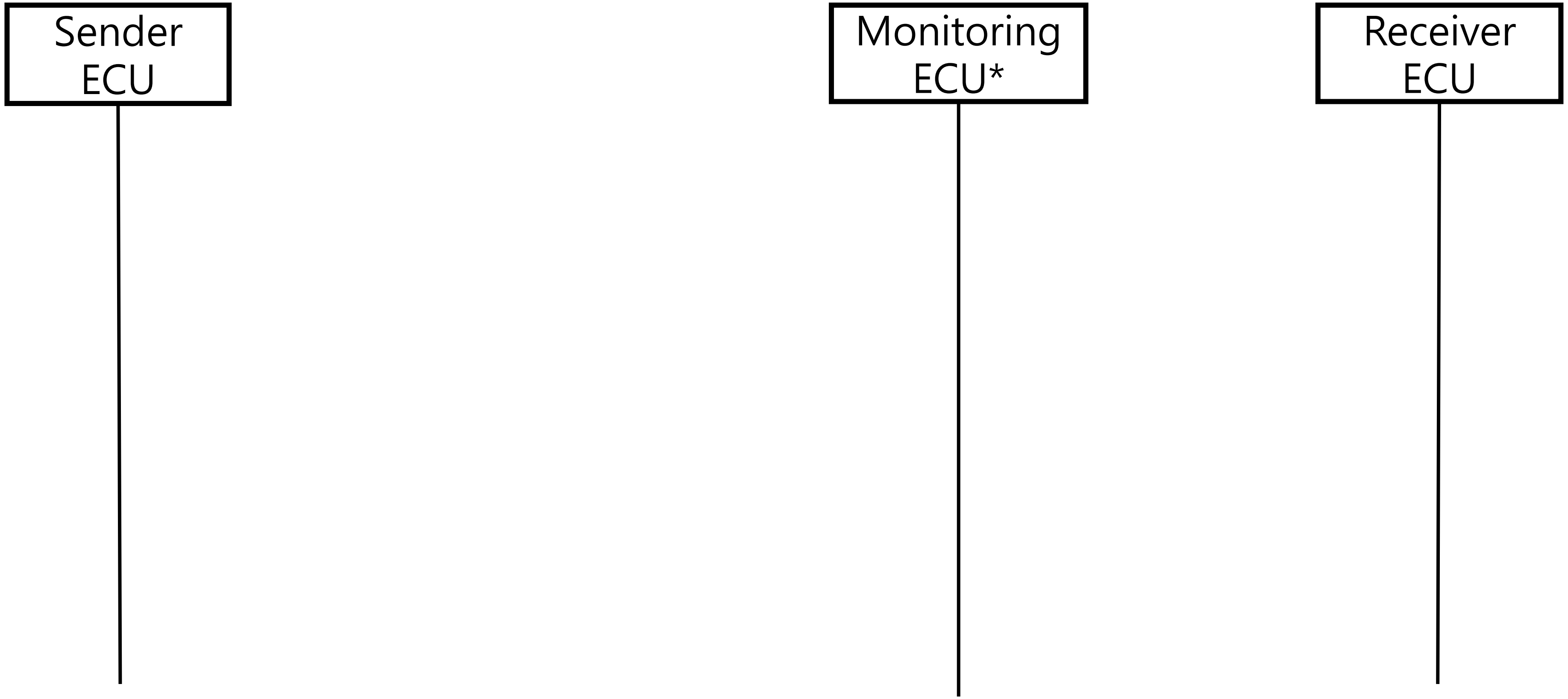
Our Solution: ShadowAuth

- Flexible authentication packets
- HMAC
- Asynchronous authentication
- Binary patching

"Accept-first-authenticate-later"

ShadowAuth Design

ShadowAuth Design



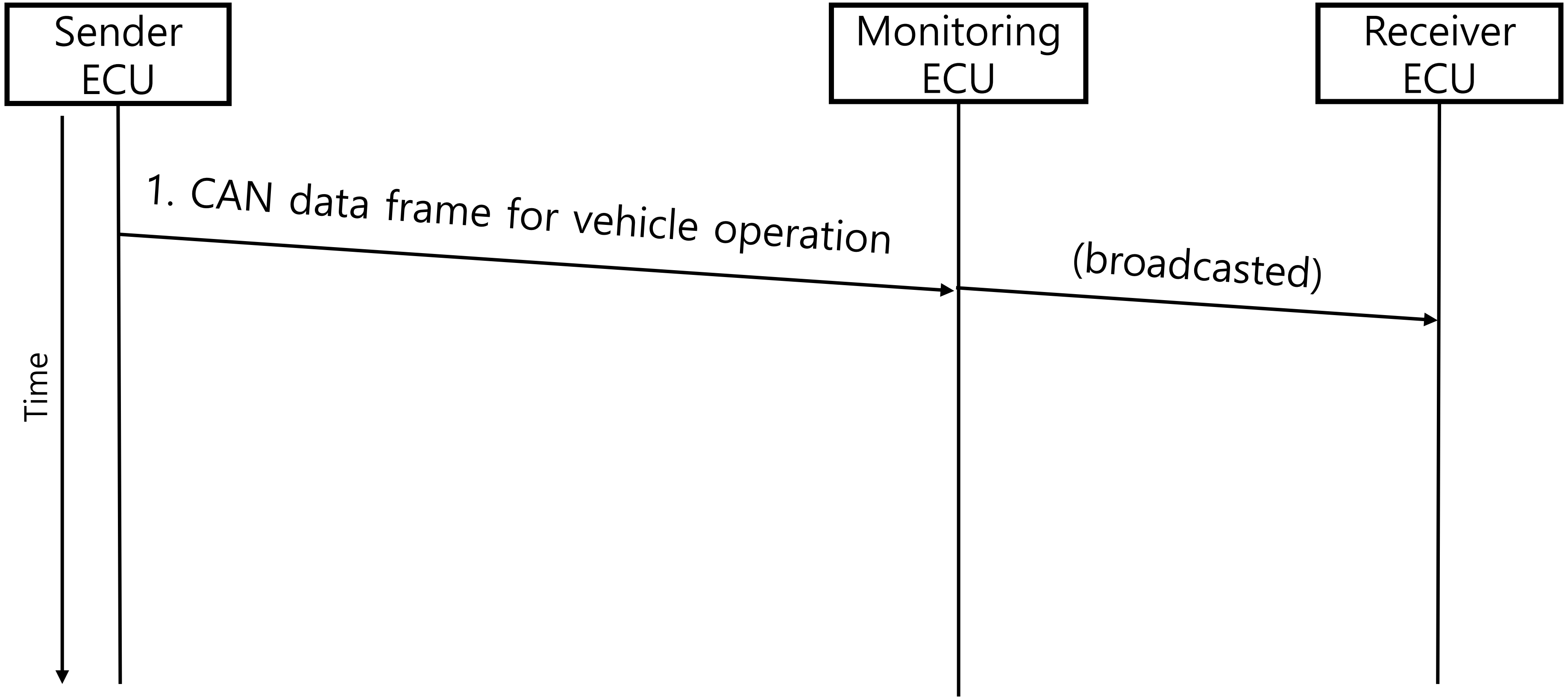
Sender ECU

Monitoring ECU*

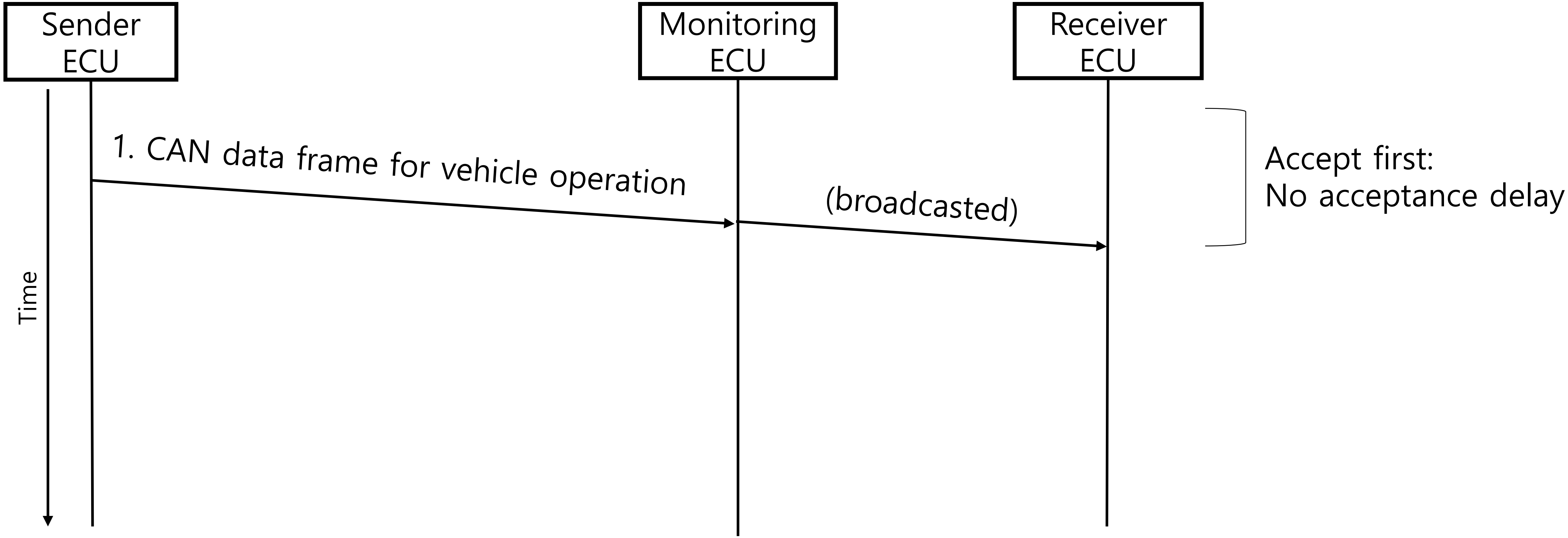
Receiver ECU

*E.g., Gateway ECUs

ShadowAuth Design



ShadowAuth Design



Sender ECU

Monitoring ECU

Receiver ECU

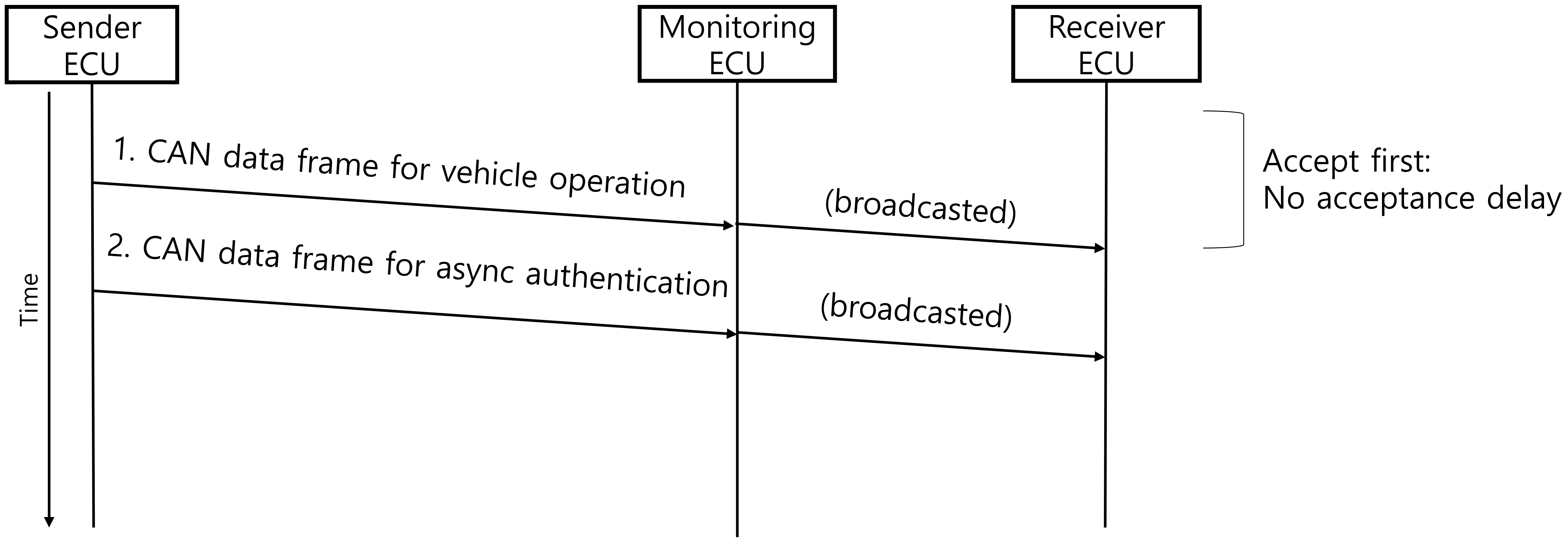
Time

1. CAN data frame for vehicle operation

(broadcasted)

Accept first:
No acceptance delay

ShadowAuth Design



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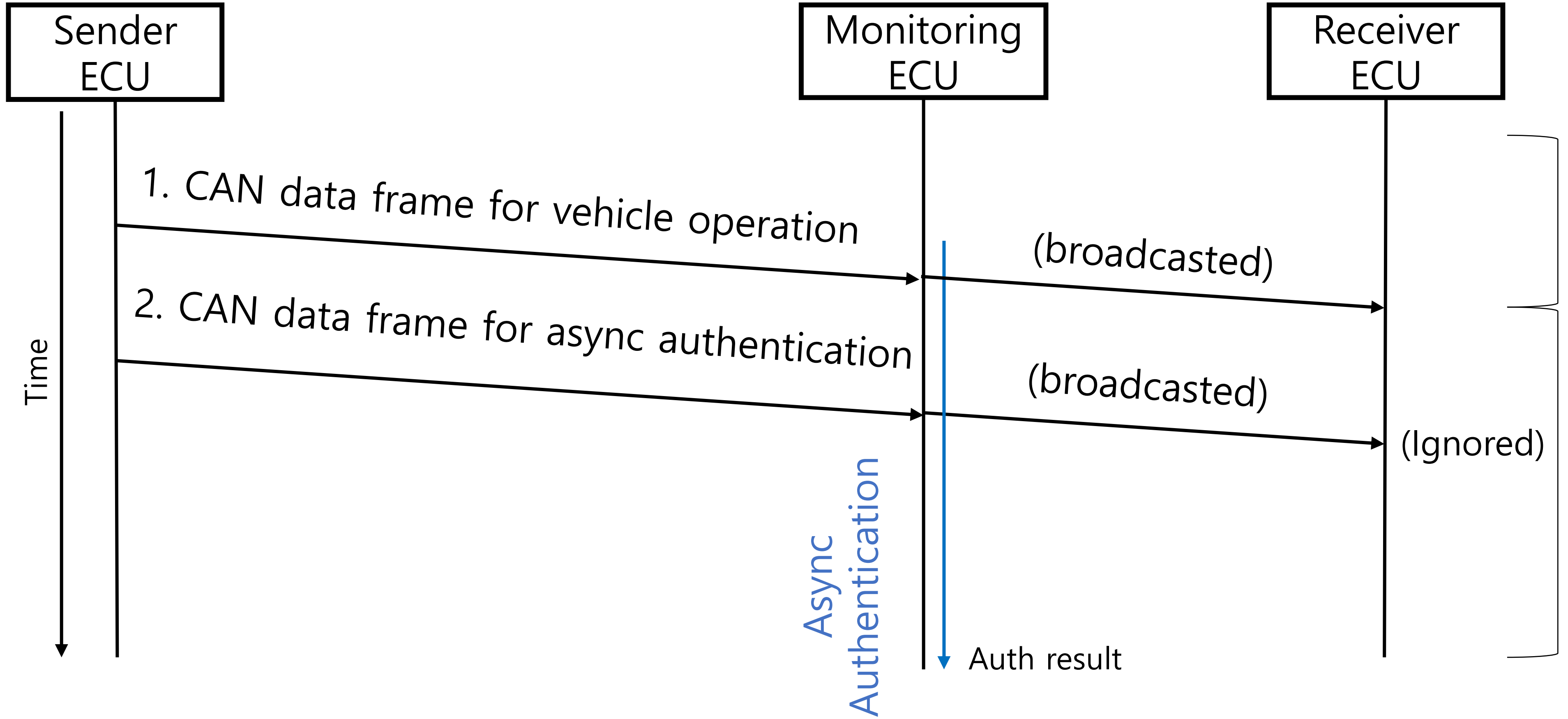
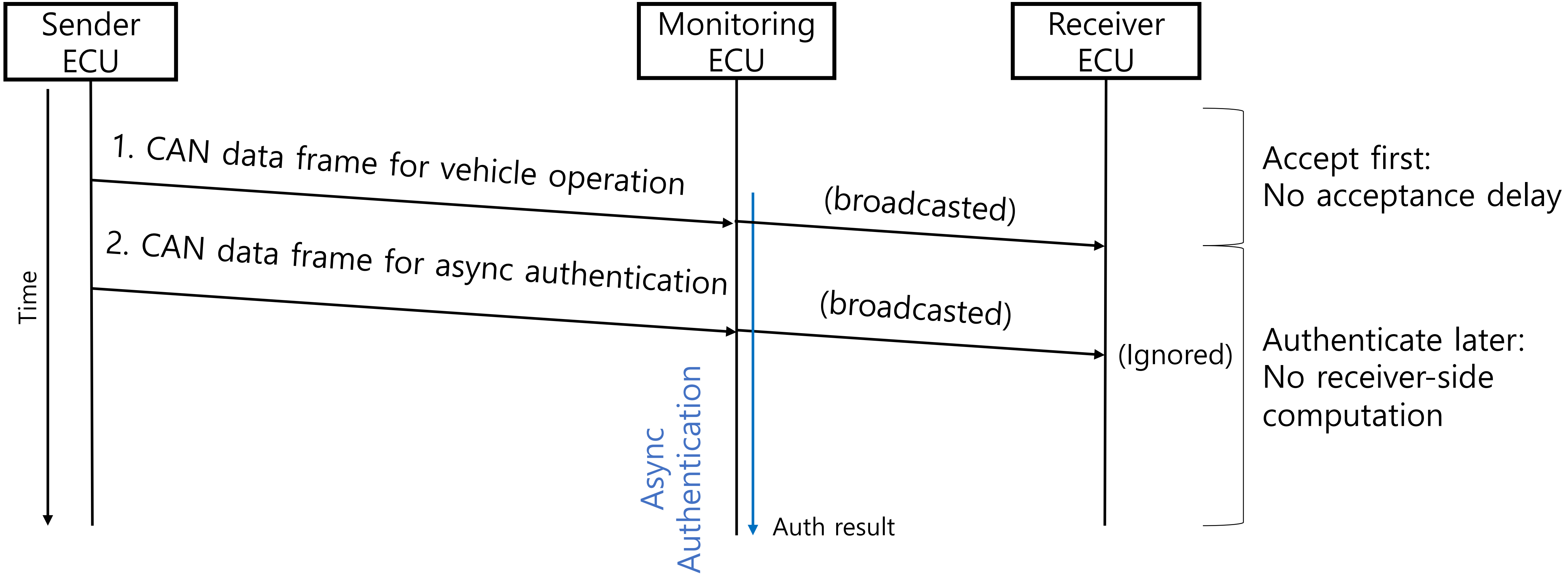


Accept first:
No acceptance delay

Authenticate later:
No receiver-side computation

ShadowAuth Design

"Accept-first-authenticate-later"



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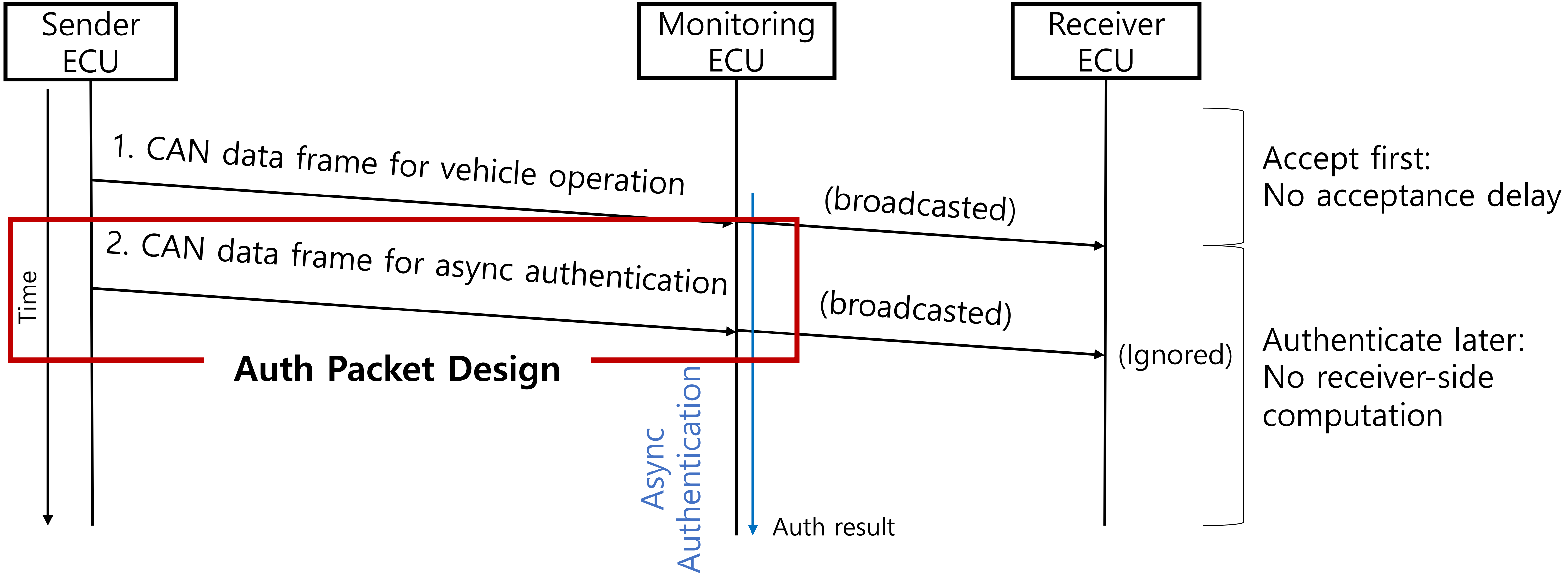
"Accept-first-authenticate-later"



ShadowAuth Design

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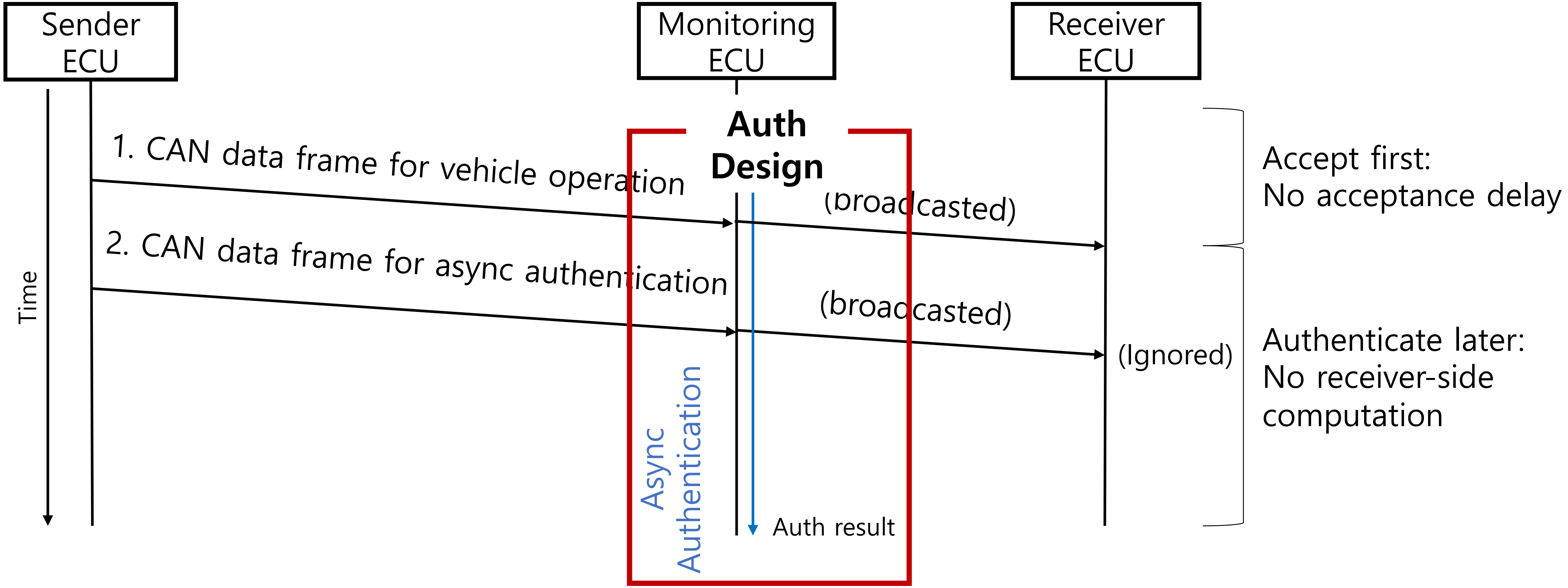
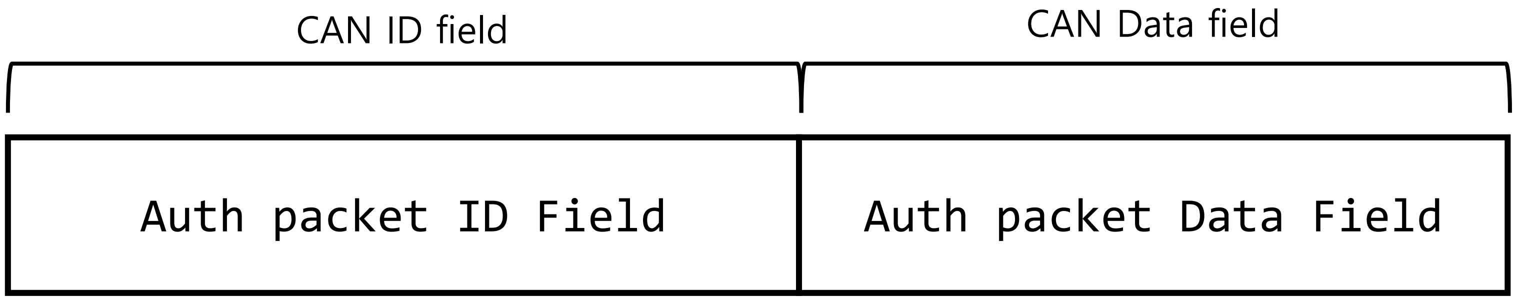


Authentication Packet Design

- Design goal
  - Compatible with existing protocols
  - Minimize impact on existing systems
  - Tolerate known attacks



CAN ID field

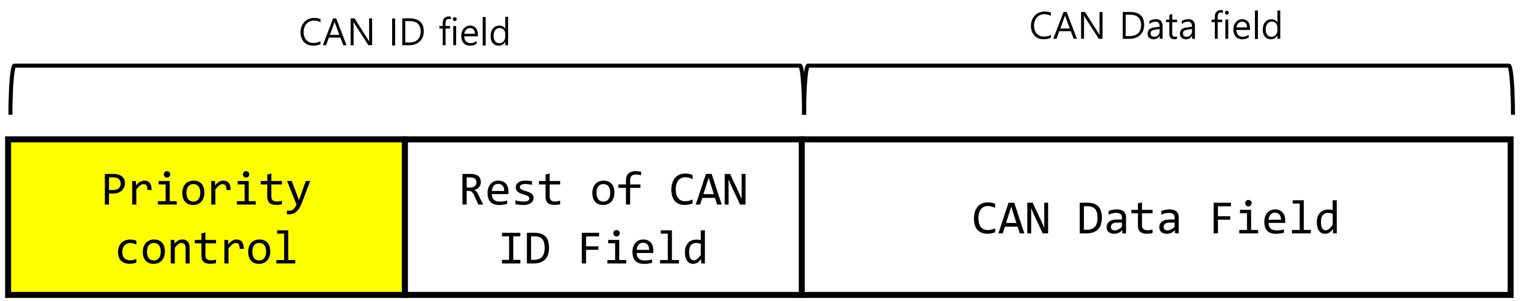
CAN Data field

Auth packet ID Field

Auth packet Data Field

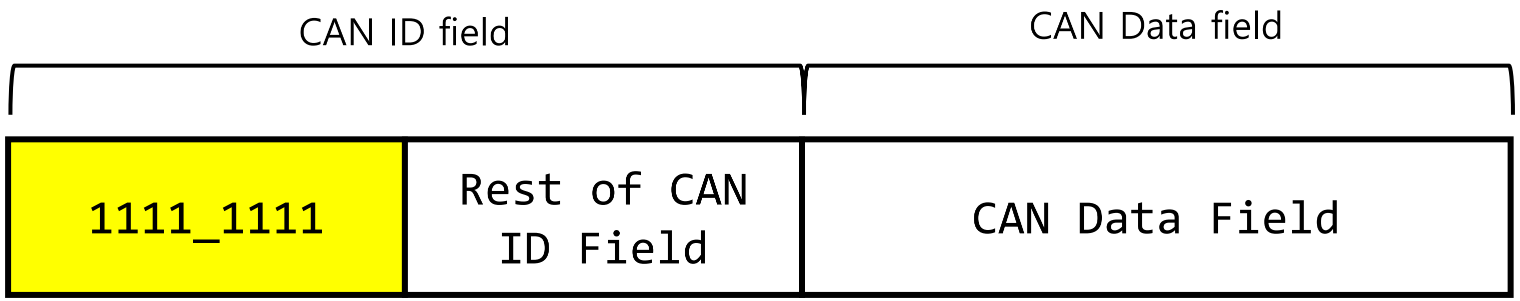
Authentication Packet Design

- Priority Control Field: Variable Length of Sequential Recessive Bits (1)
  - Make packets compatible with existing protocols
  - Minimize impact on existing systems: always yield the bus to op packets



Authentication Packet Design

- Concrete Example: J1939 Standard
  - Authentication packets start with sequential eight recessive bits
  - No J1939 packet starts with those eight



CAN ID field

CAN Data field

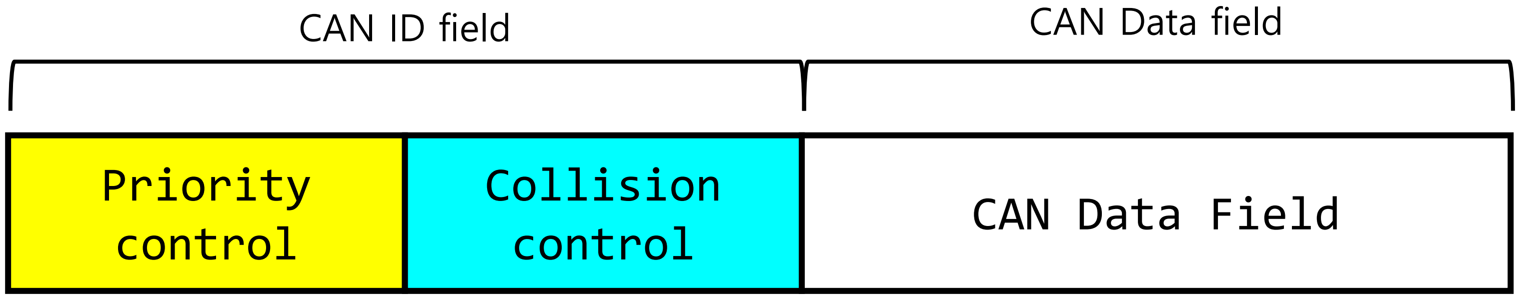
1111_1111

Rest of CAN ID Field

CAN Data Field

Authentication Packet Design

- Collision Control Field: Randomized Field
  - Avoid collision among auth packets
  - Hide auth packets from attackers
  - Tolerate to op-auth pair recovery attacks



CAN ID field

CAN Data field

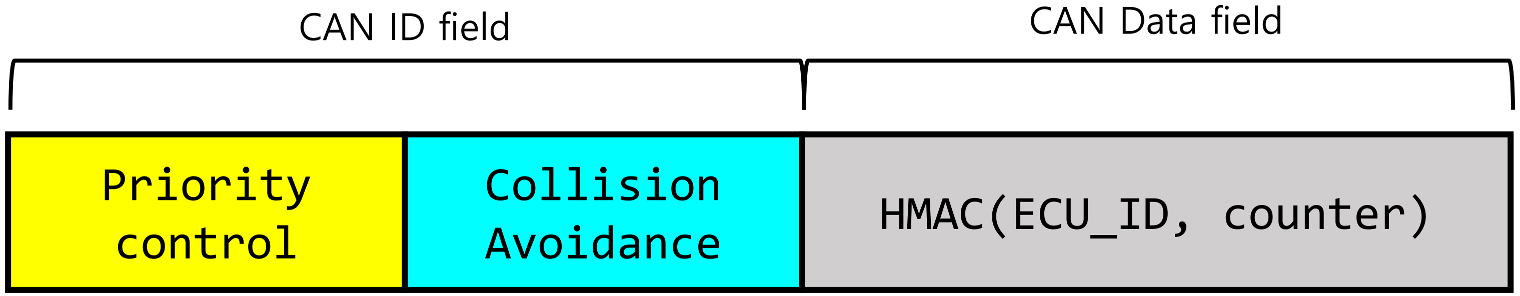
Priority control

Collision control

CAN Data Field

Authentication Packet Design

- Data Field: HMAC (Blake3)
  - Sender authentication with a unique ECU ID
  - Tolerate to replay attacks: increasing counter
  - Minimize potential impact on existing systems
    - Minimize firmware patching: no access to firmware-side data (e.g., CAN ID)
    - Minimize traffic increase by using a single packet for auth



CAN ID field

CAN Data field

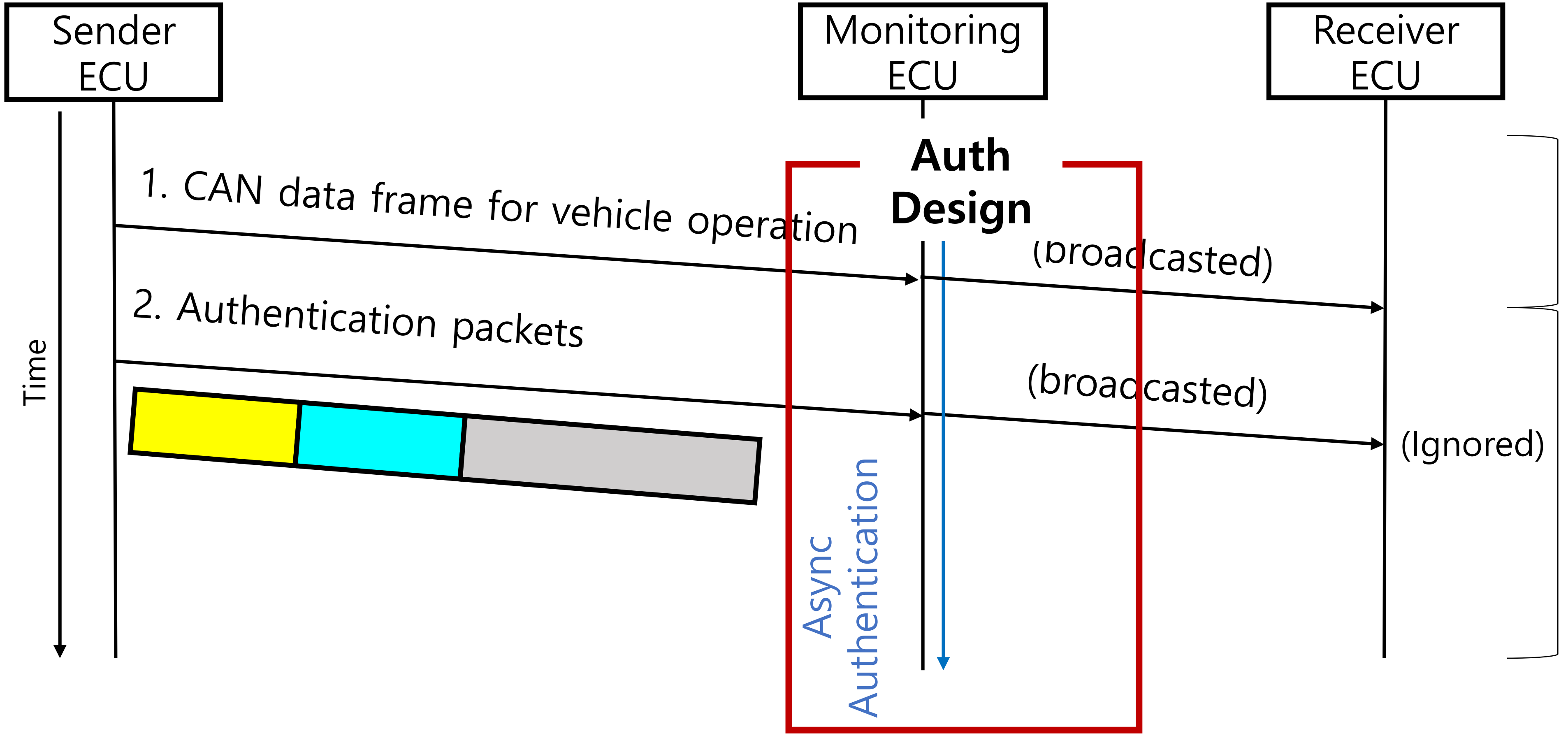
Priority control

Collision Avoidance

HMAC(ECU_ID, counter)

ShadowAuth Design

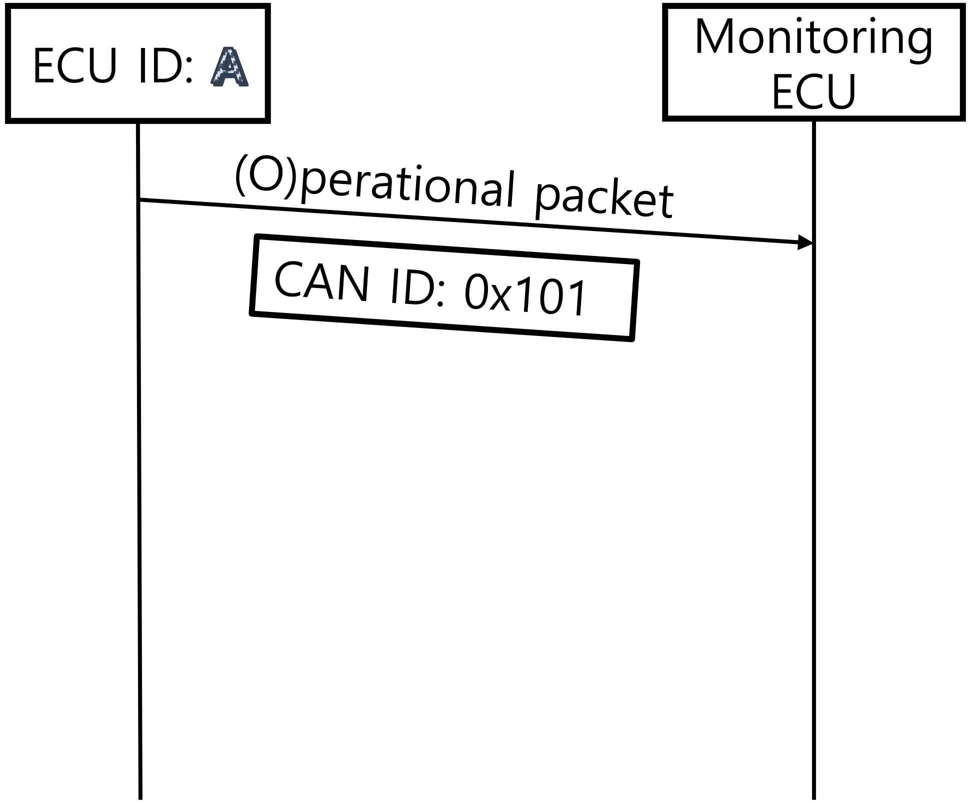
"Accept-first-authenticate-later"



Accept first:
No acceptance delay

Authenticate later:
No receiver-side computation

Authentication Design



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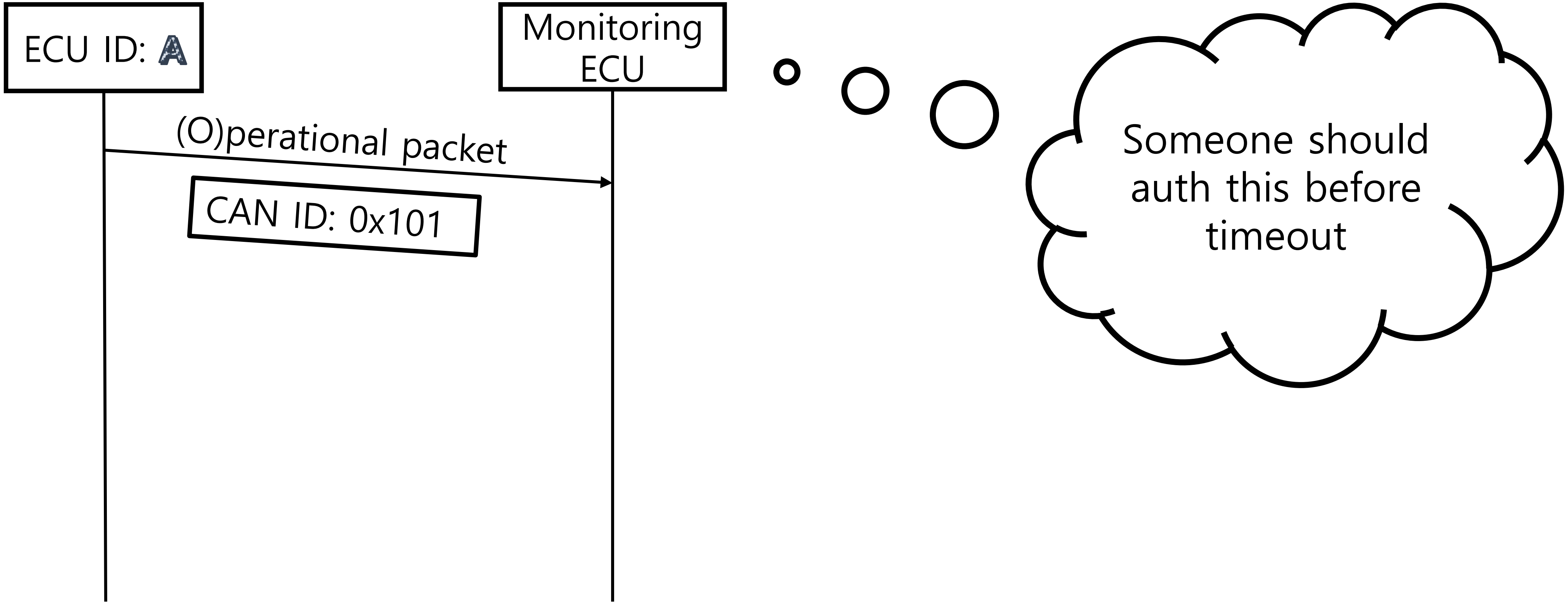

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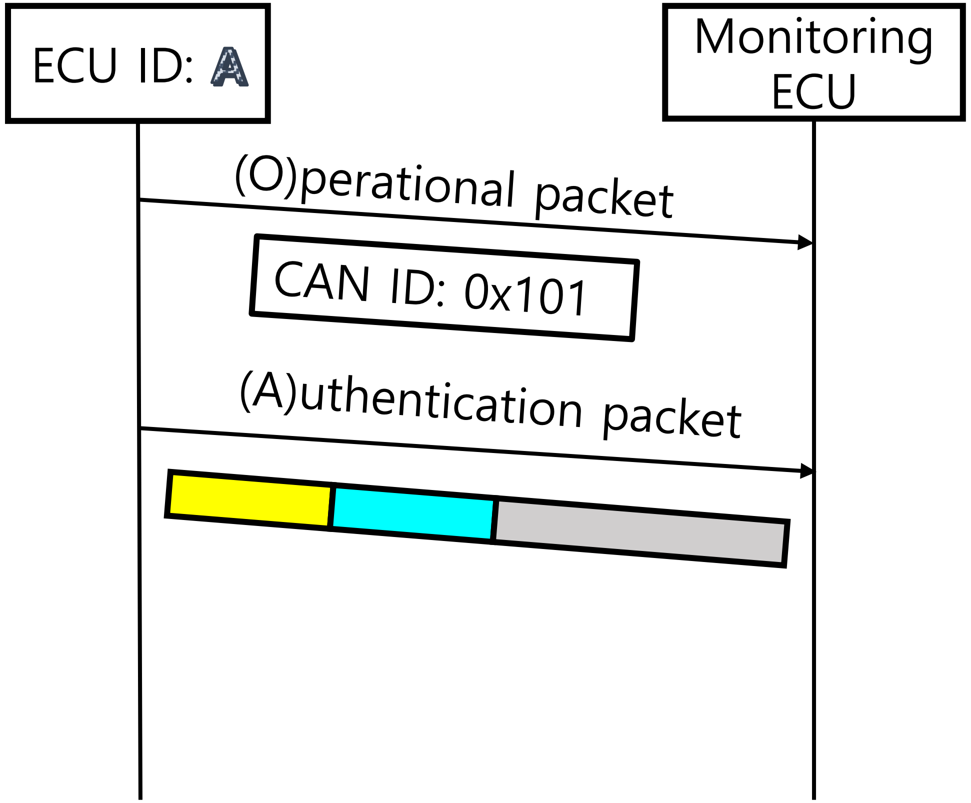

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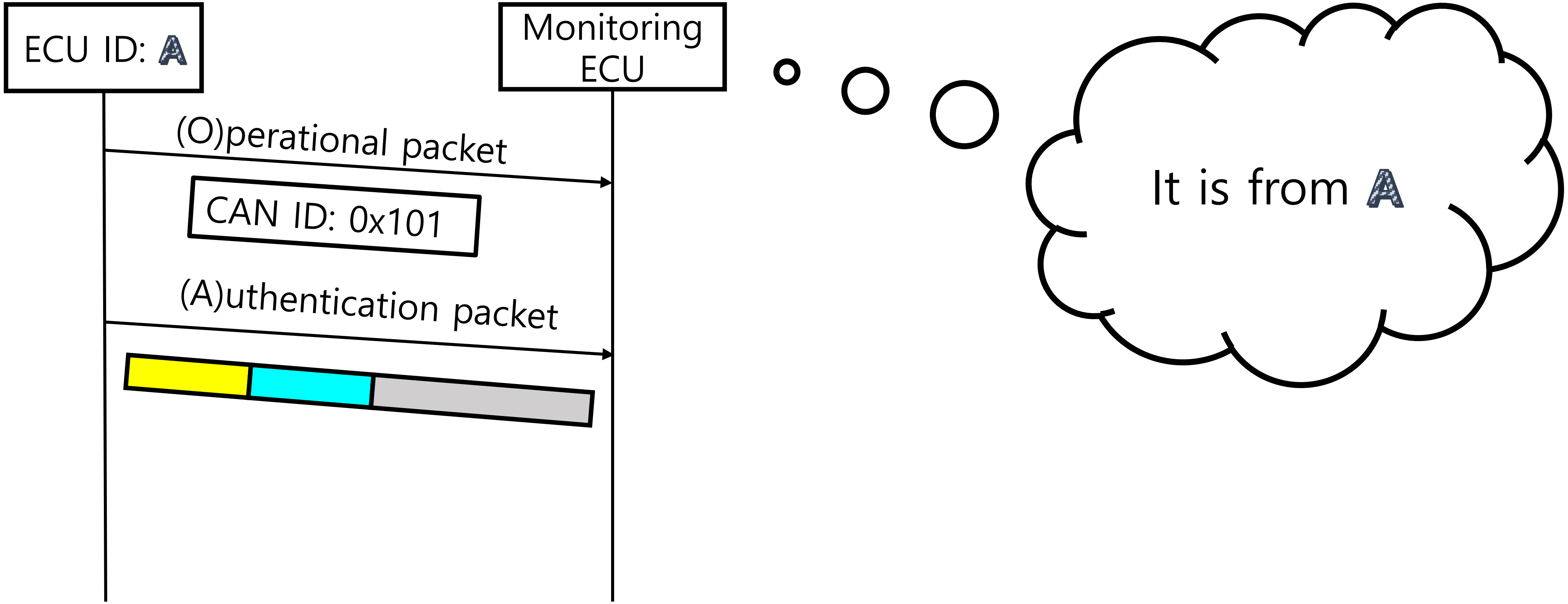


ECU ID: A

Monitoring ECU

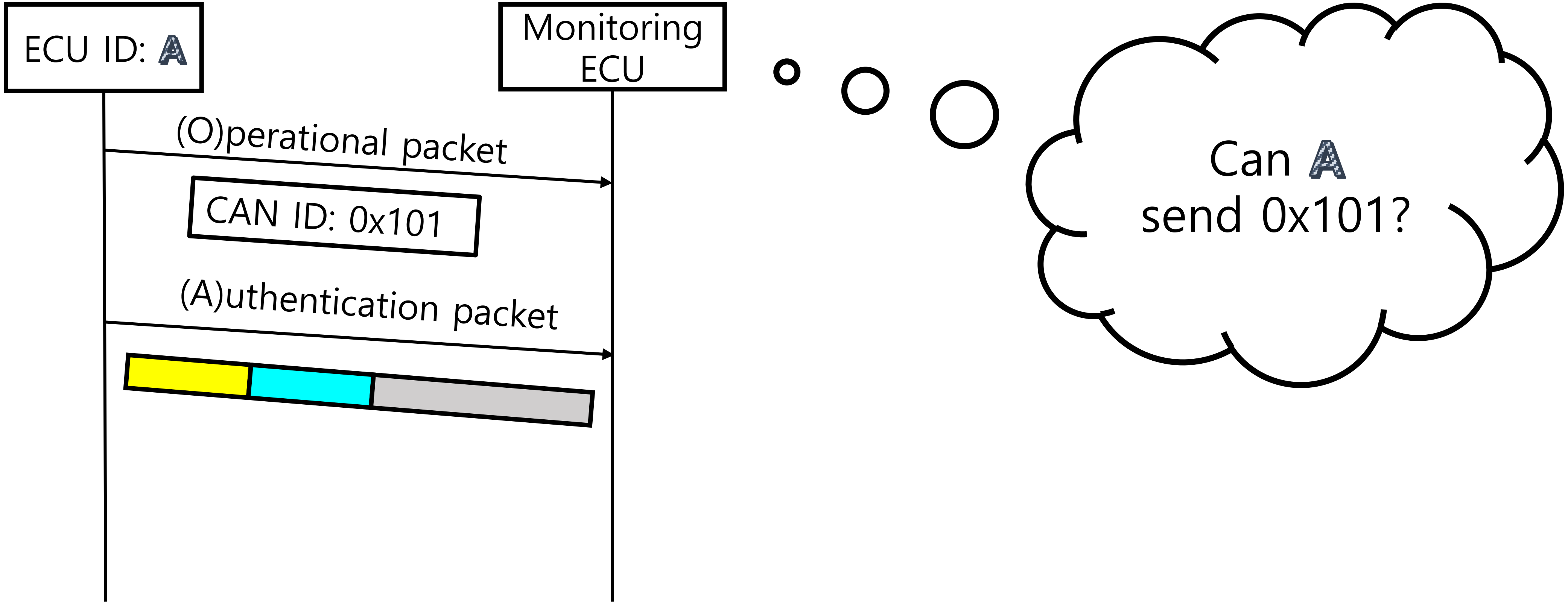
(O)perational packet

CAN ID: 0x101

(A)uthentication packet

It is from A

Authentication Design



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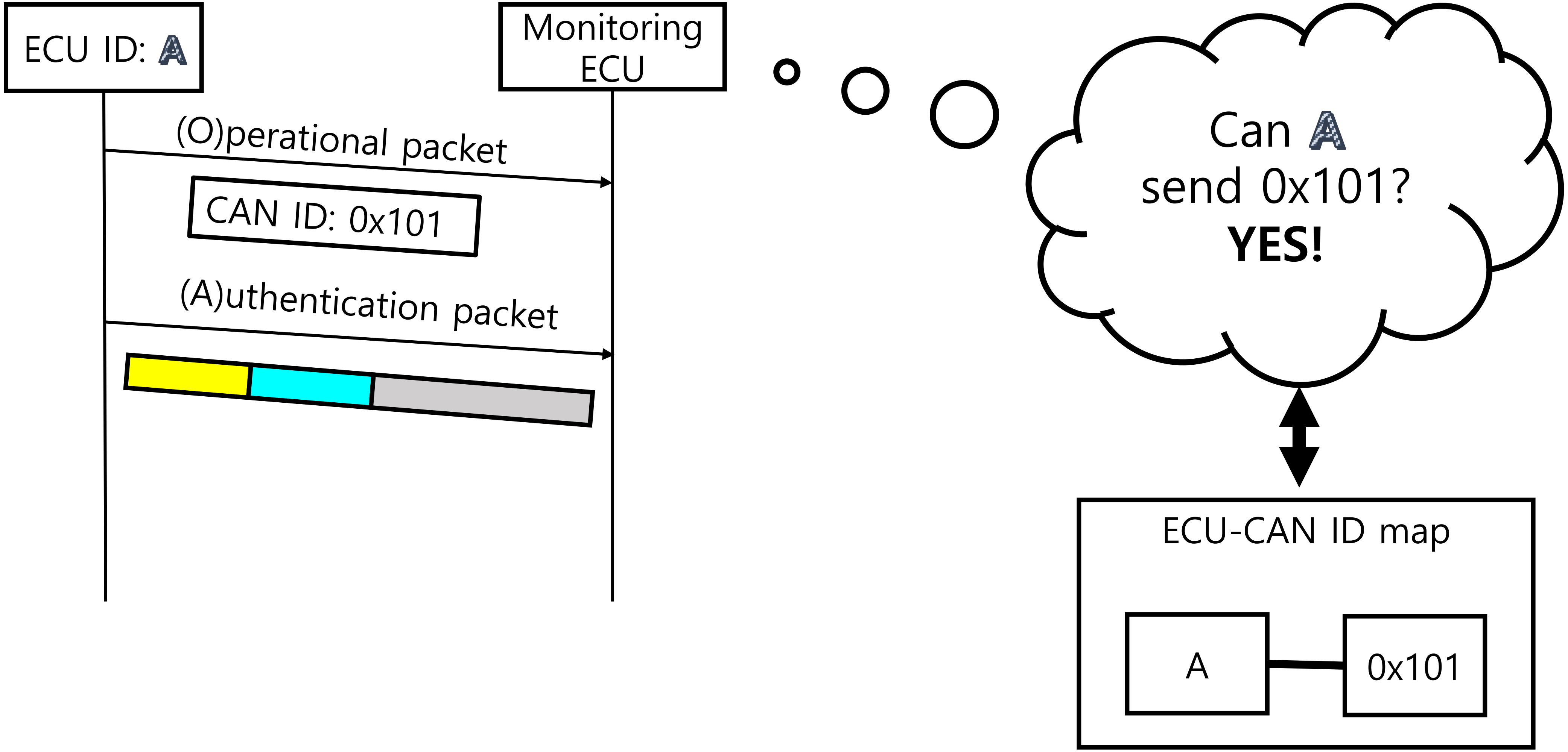

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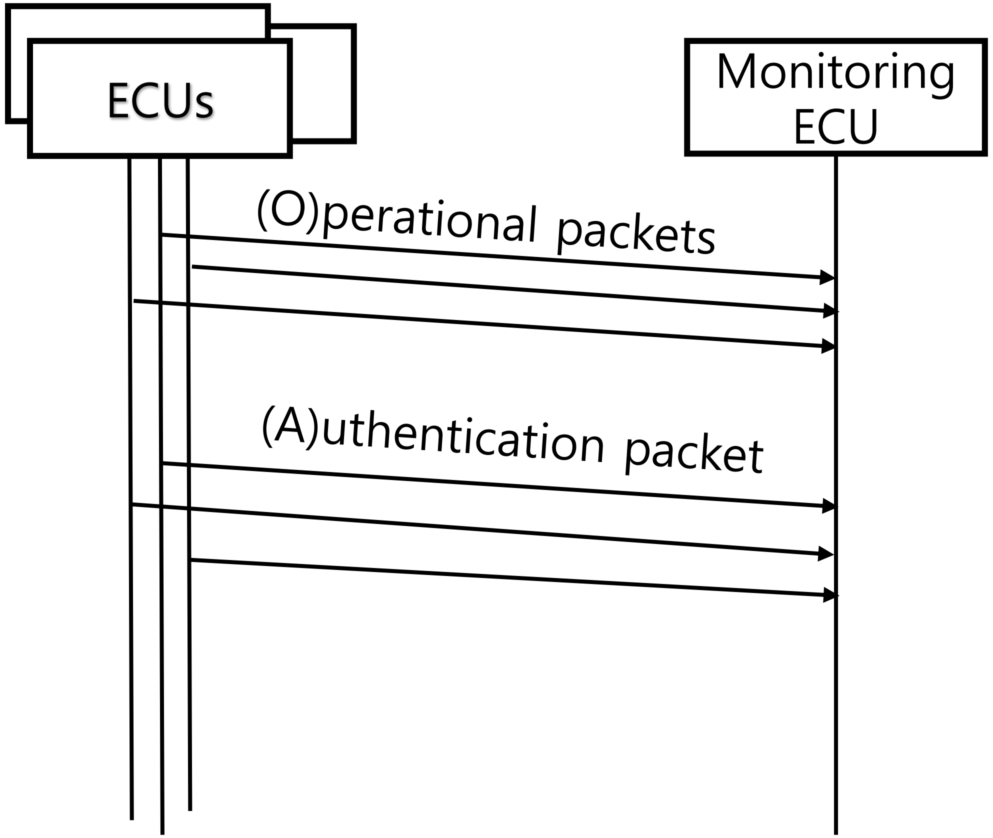

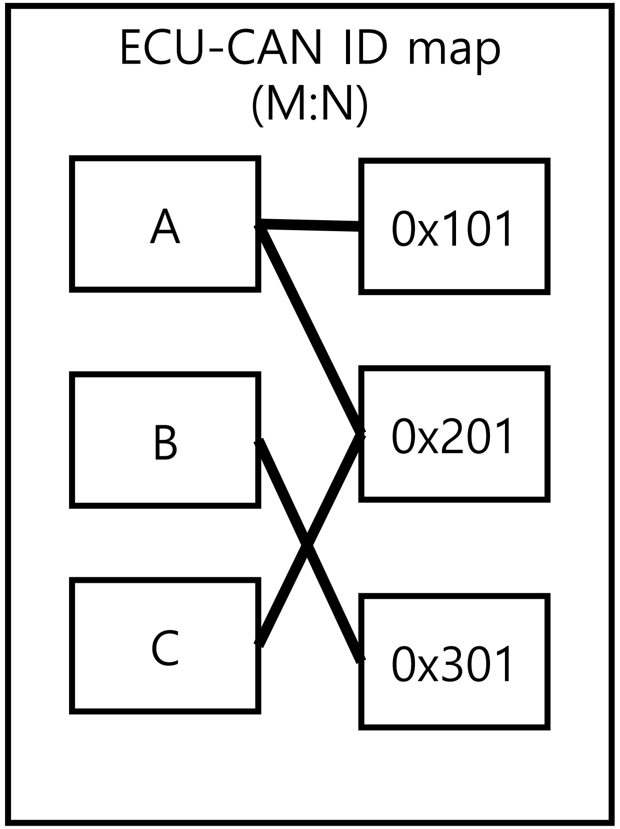

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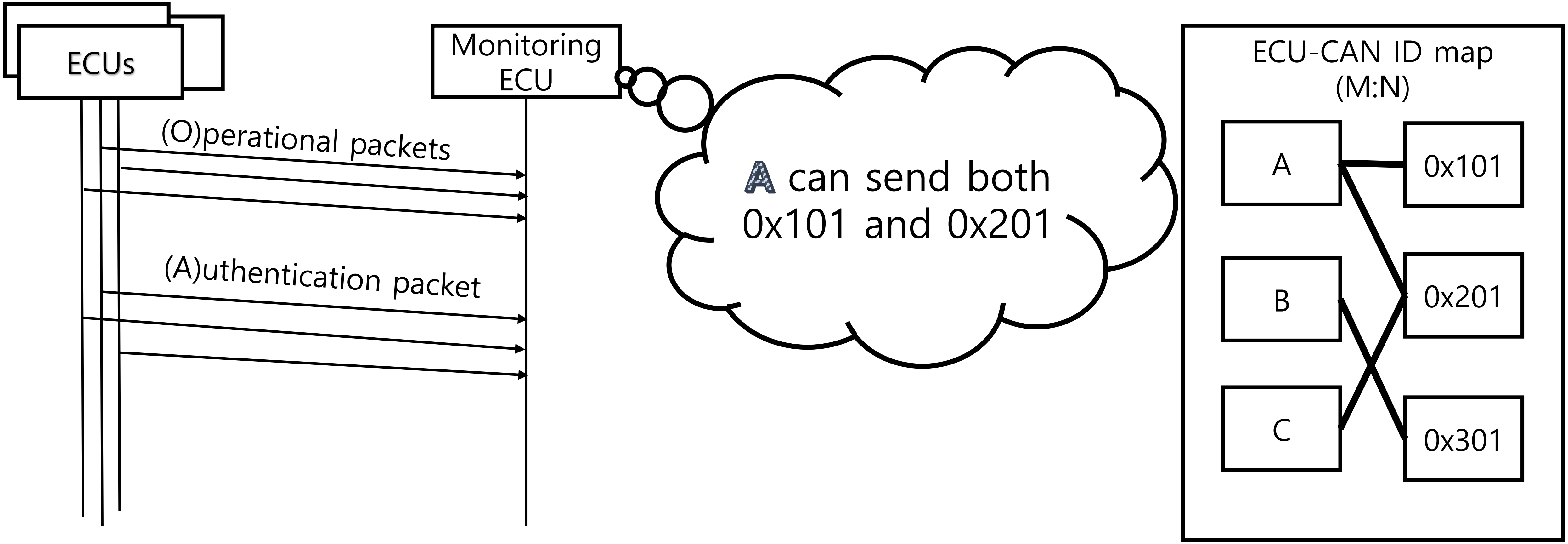

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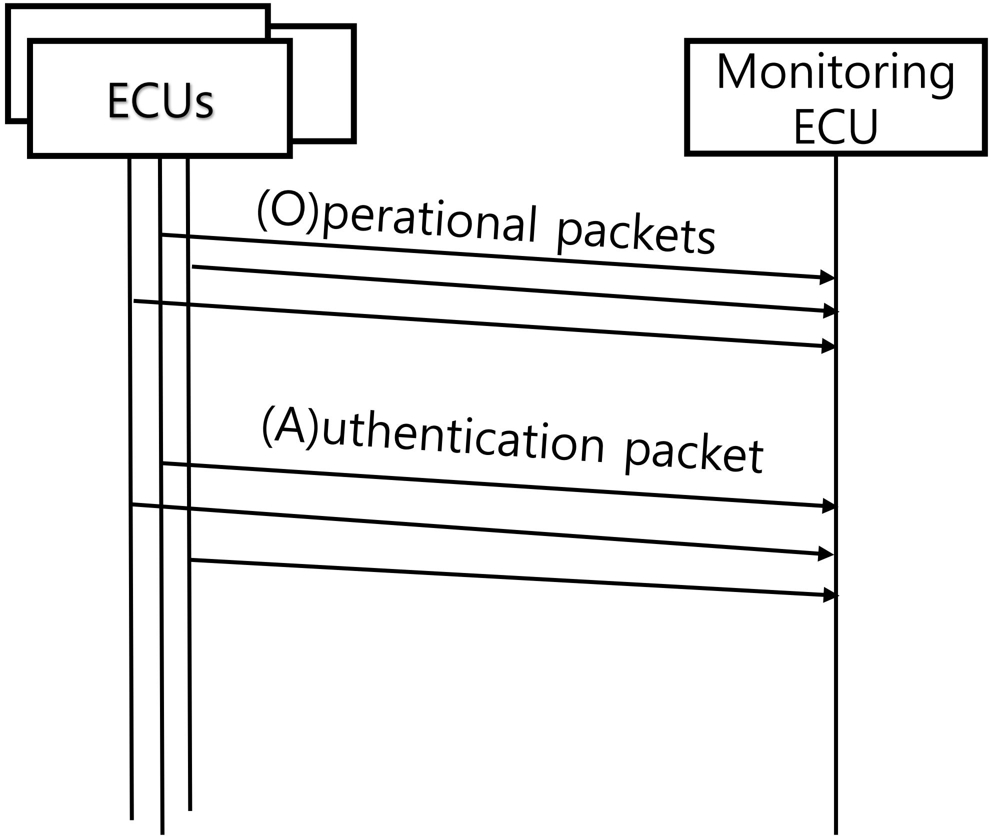


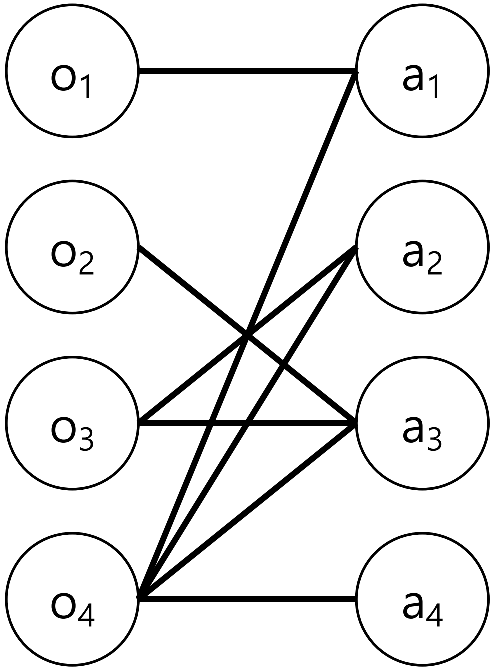
ECUs

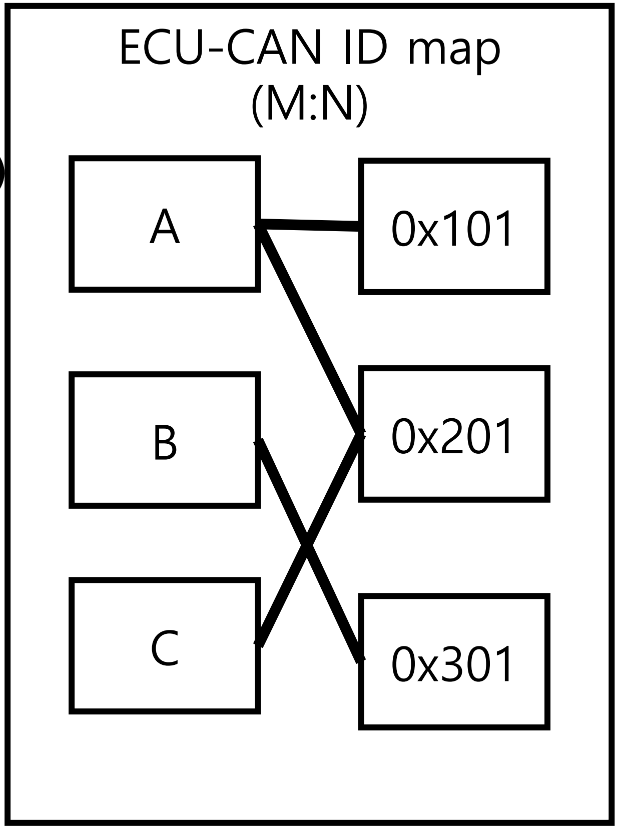
Monitoring ECU

(O)perational packets

(A)uthentication packet

Too many possible scenarios





ECU-CAN ID map (M:N)

A

B

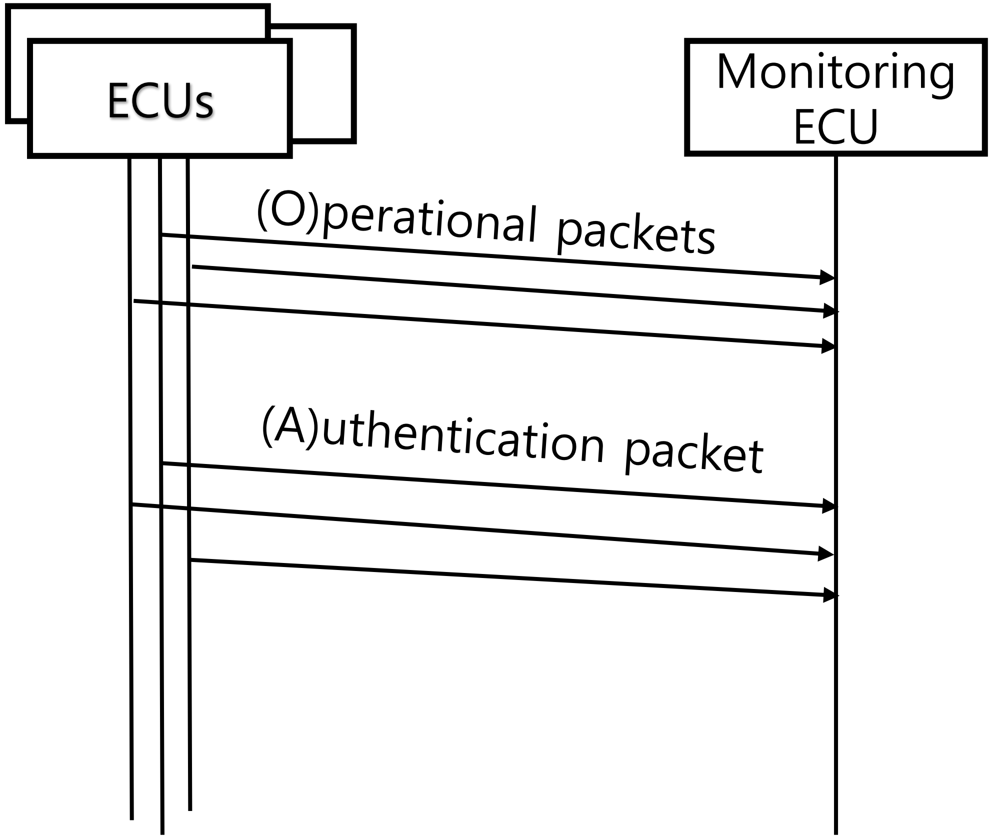
C

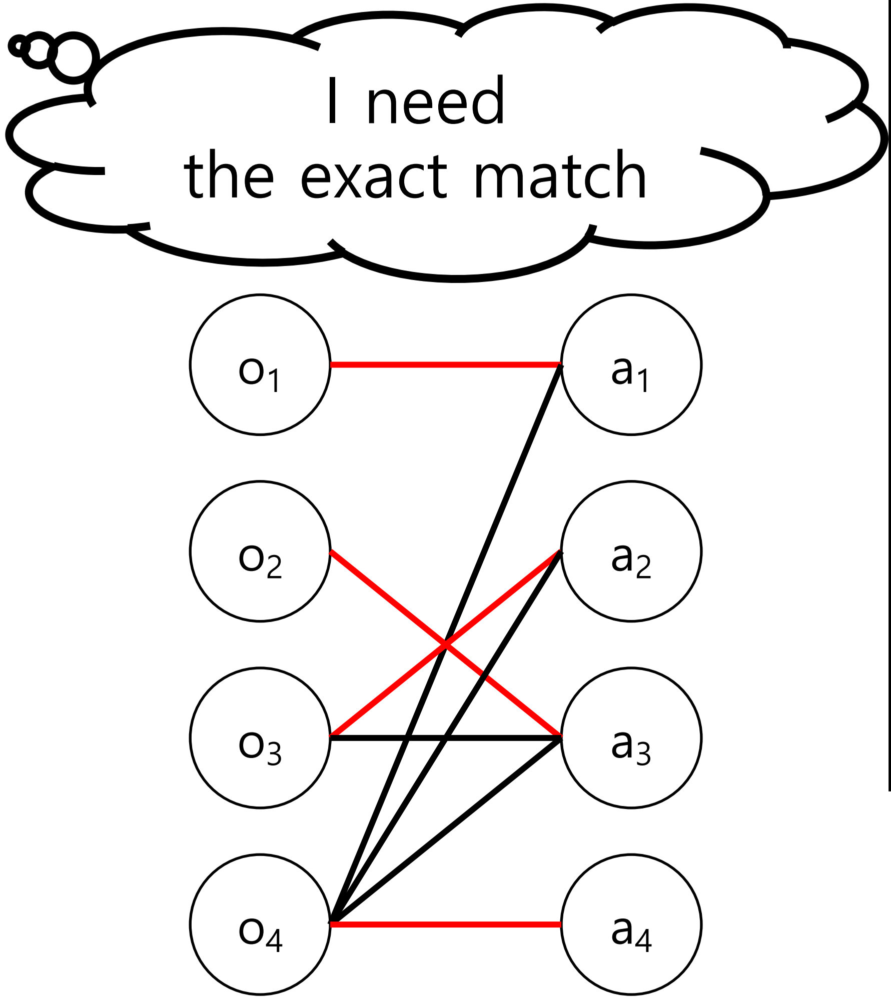
0x101

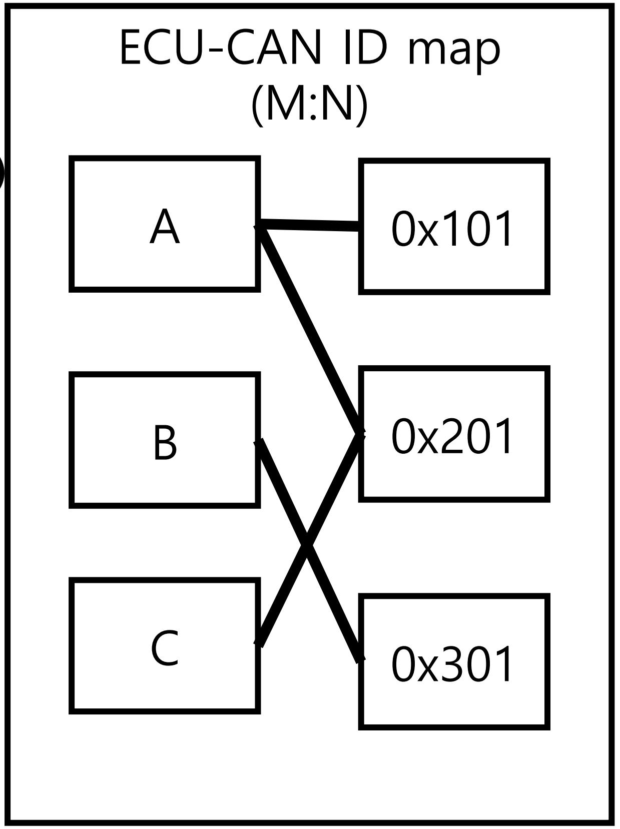
0x201

0x301

Authentication Design

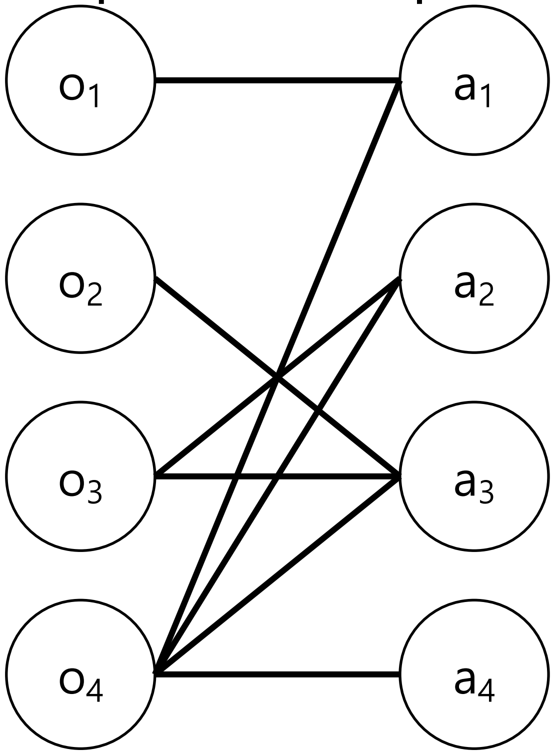




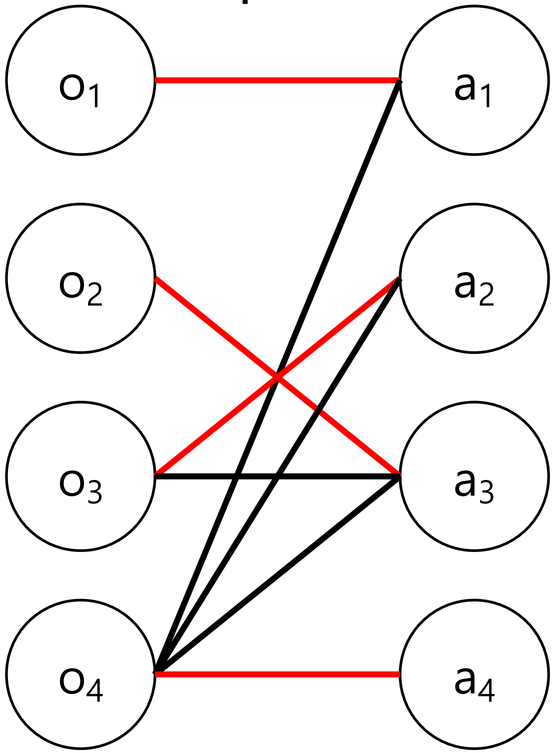


Authentication Design

- Observation: maximum matching should be equal to the number of auth packets
    - If no attack presents, operational and authentication packets are sent once



Bipartite graph

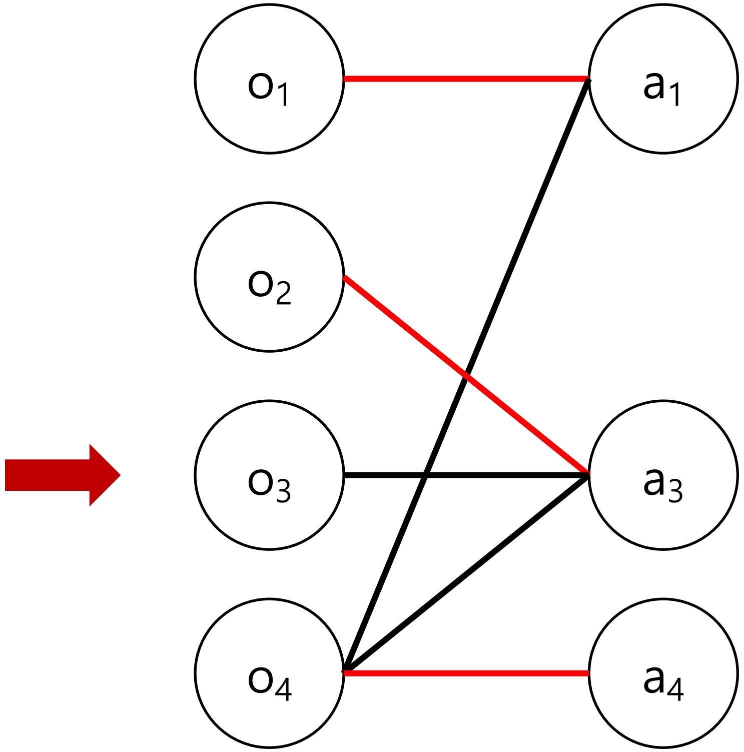


Maximum matching (red)

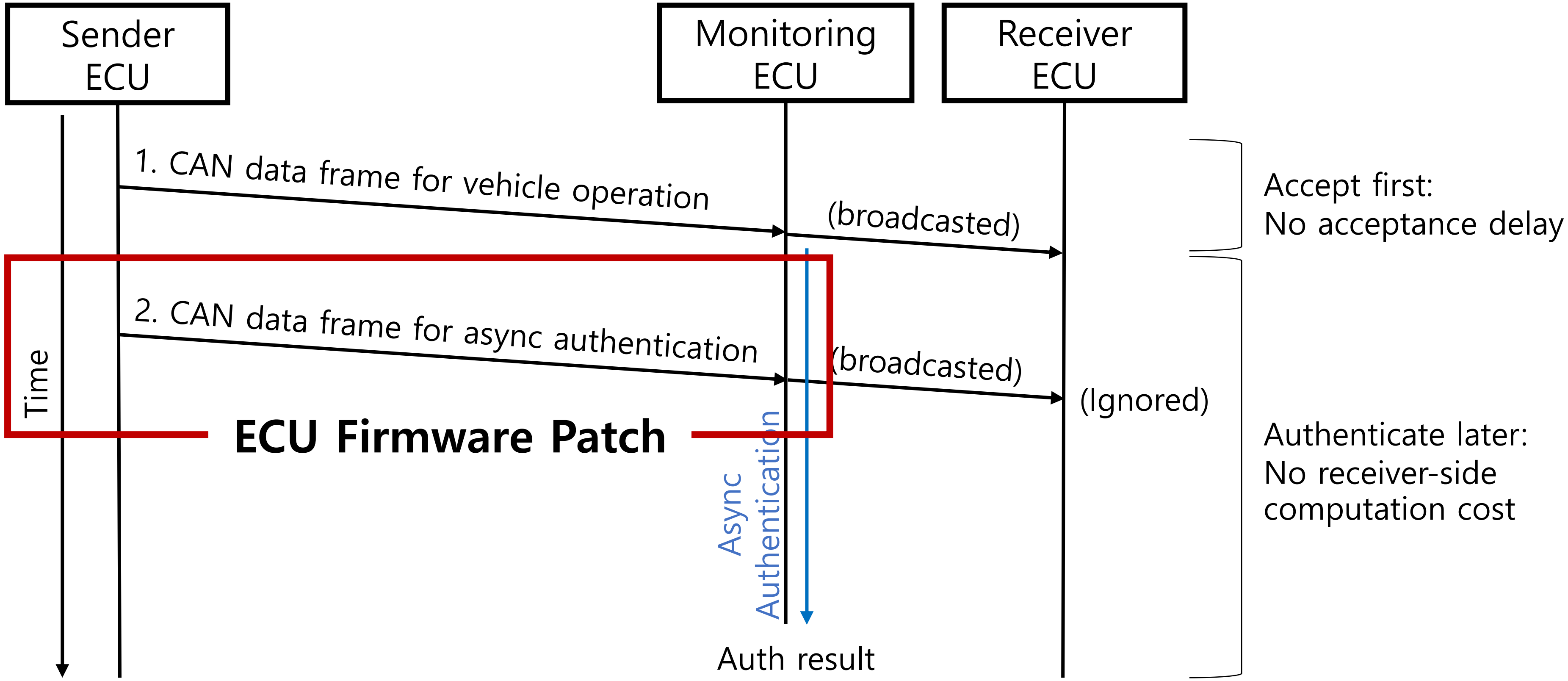
Authentication Design

- Attack scenario: Operational packet fabrication

O_3 does not match with any of auth packet!
We are under attacks!



ShadowAuth Design

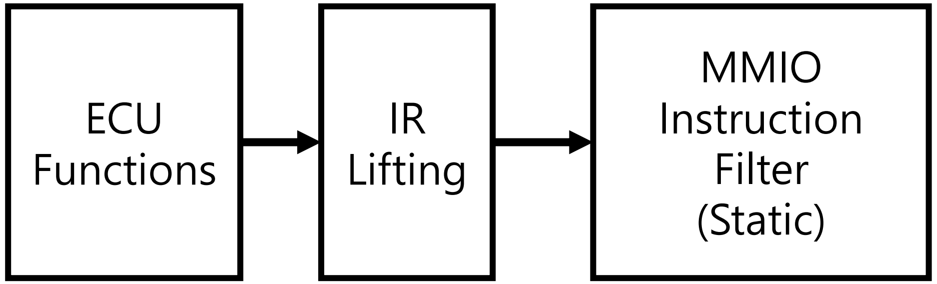


- Where: Every instruction next to `call can_tx`
- How: trampoline-based patching

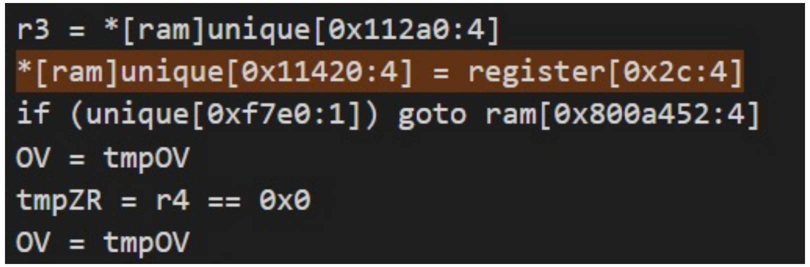
ECU Firmware Patch

- Goal:
  - Automation for finding the CAN Tx function
  - Independent to architecture
- Solution:
  - Check the MMIO instruction’s volume

ECU Firmware Patch

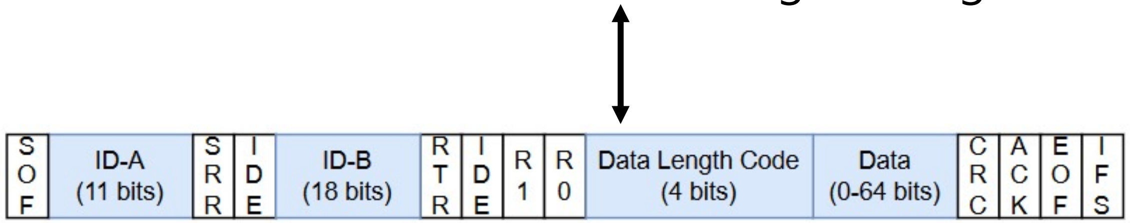


- Static analysis



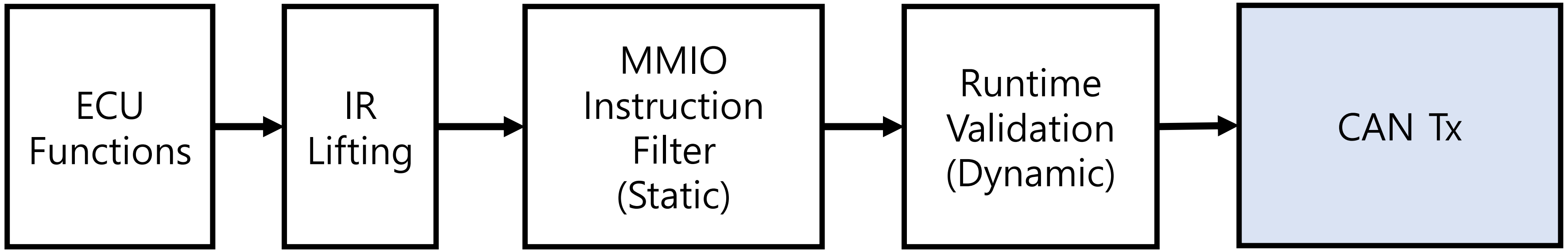
```
r3 = *[ram]unique[0x112a0:4]
*[ram]unique[0x11420:4] = register[0x2c:4]
if (unique[0xf7e0:1]) goto ram[0x800a452:4]
OV = tmpOV
tmpZR = r4 == 0x0
OV = tmpOV
```

MMIO instructions are large enough to send CAN packet?

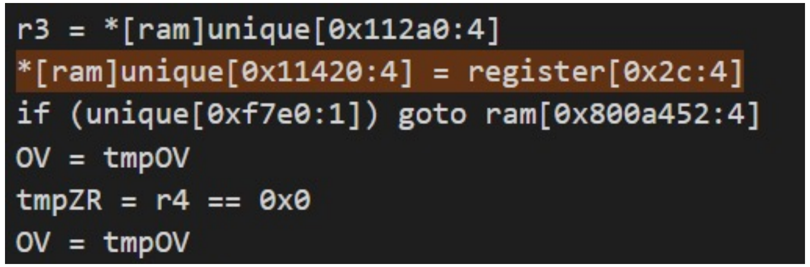


SOF	ID-A (11 bits)	SRR	IDE	ID-B (18 bits)	RTR	IDE	R1	R0	Data Length Code (4 bits)	Data (0-64 bits)	CRC	ACK	EOF	IFS

ECU Firmware Patch


ECU Functions
IR Lifting
MMIO Instruction Filter (Static)
Runtime Validation (Dynamic)
CAN Tx

- Static analysis



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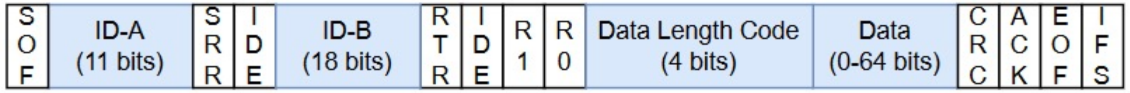
```

- Dynamic Analysis
  - Monitor the actual CAN bus
  - Run functions

MMIO instructions are large enough to send CAN packet?



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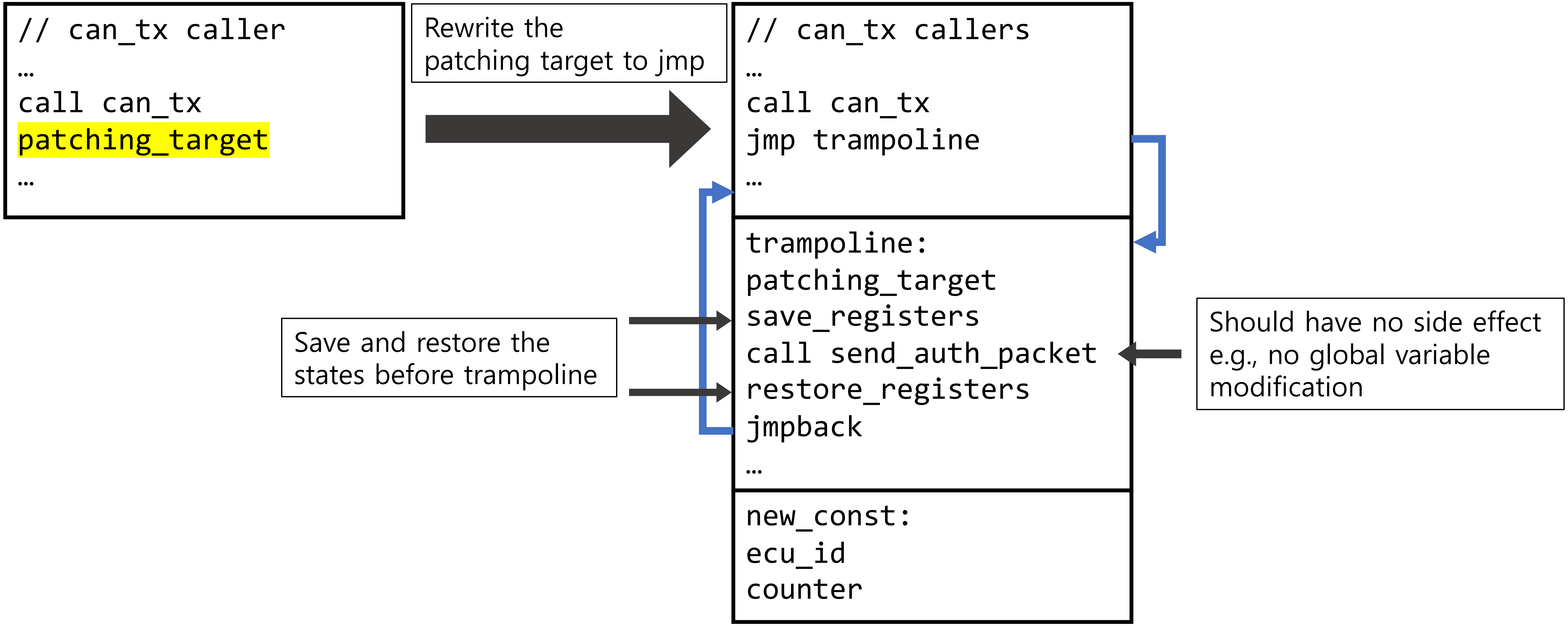
ECU Firmware Patch

Trampoline-based patch



```
// can_tx caller
…
call can_tx
patching_target
…
```

Rewrite the patching target to jmp

```
// can_tx callers
…
call can_tx
jmp trampoline
…
```

```
trampoline:
patching_target
save_registers
call send_auth_packet
restore_registers
jmpback
…
```

```
new_const:
ecu_id
counter
```

Save and restore the states before trampoline

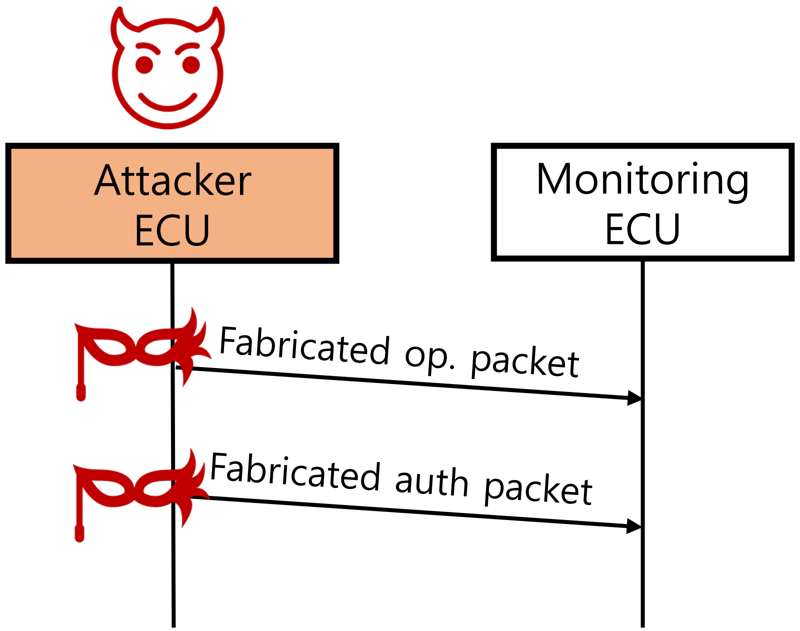
Should have no side effect e.g., no global variable modification

Evaluation

- Open-source ECU firmware: rusEFI, Rabbit ECU, Styreehet
- Real-world CAN traffic: 2014 Kenworth T270 / 2015 Kenworth T660 (>37M packets)
- Static analysis: 100% accuracy (confirmed by dynamic analysis)
- Asynchronous authentication: 14ms (worst)
- Space overhead (~~182KB~~ 84KB by Blake3)

Evaluation: Case Study

- Case 1: Impersonation attack
  - Auth fails: ECU_ID is unknown

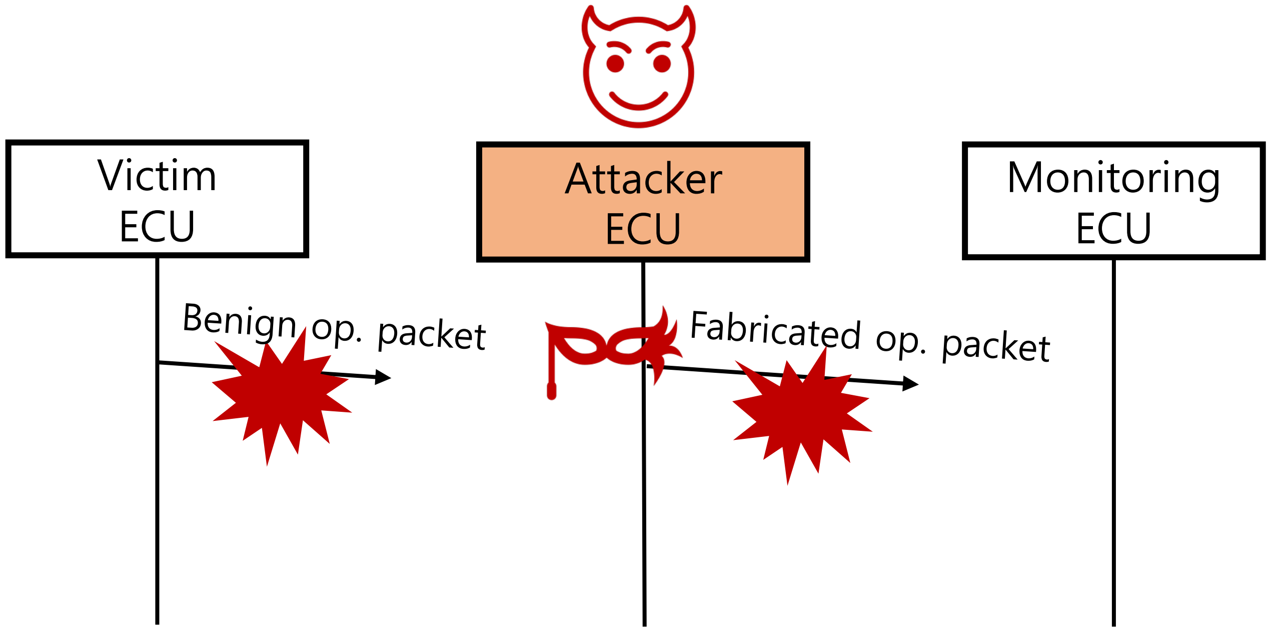


Priority control	Anonymity control	HMAC(ECU_ID, counter)

Authentication packet

Evaluation: Case Study

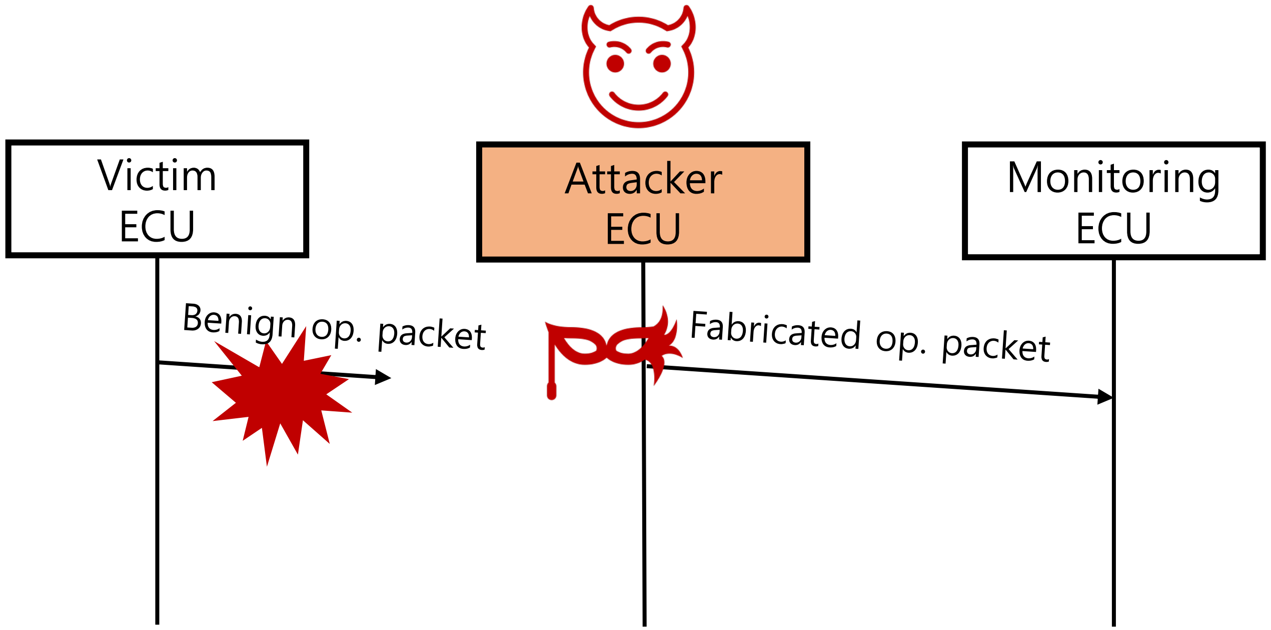
- Case 2: Bus-off attack



Make collision deliberately

Evaluation: Case Study

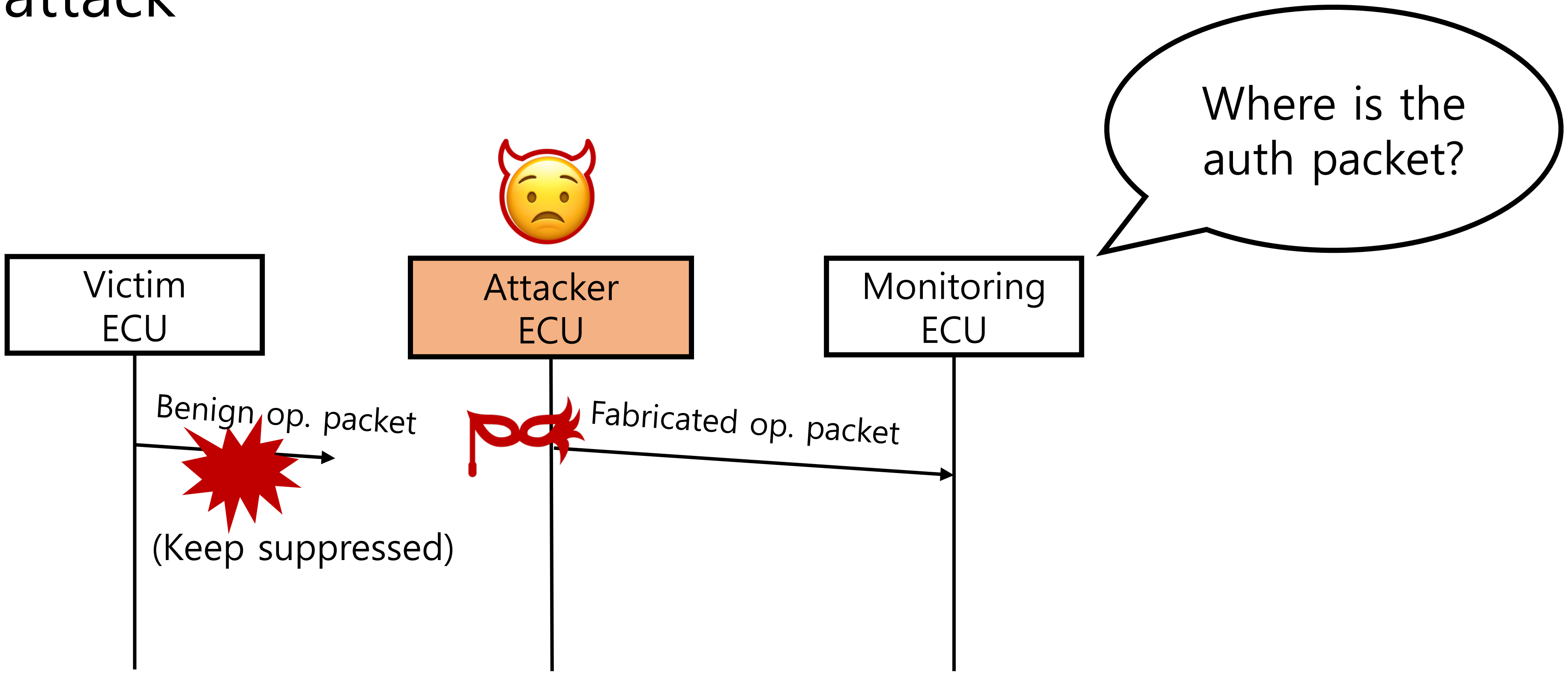
- Case 2: Bus-off attack



* The victim ECU turns into the error-passive mode first

Evaluation: Case Study

- Case 2: Bus-off attack



Limitations

- Potential impact of “accept-first”
- Recovery attacks on ECU ID, ECU-CAN ID mapping, and counter
    - E.g., firmware dump through OBD II
- Truncated Blake3 to 64-bit
- Patching real-world ECU firmware in the user side

Conclusion

- Vehicles are increasingly exposed to remote attacks
- Easily deployable solutions are required
- ShadowAuth proposes:
  - Backward-compatible CAN authentication scheme
  - Automated patch with trampoline-based binary rewriting
  - Real-time authentication with accept-first-authenticate-later policy

- Feel free to download: github.com/purseclab/ShadowAuth
  - Static analysis
  - ECU firmware patching

Thank you!

sk@purdue.edu

github.com/purseclab/ShadowAuth

PURDUE UNIVERSITY

PurSec Lab

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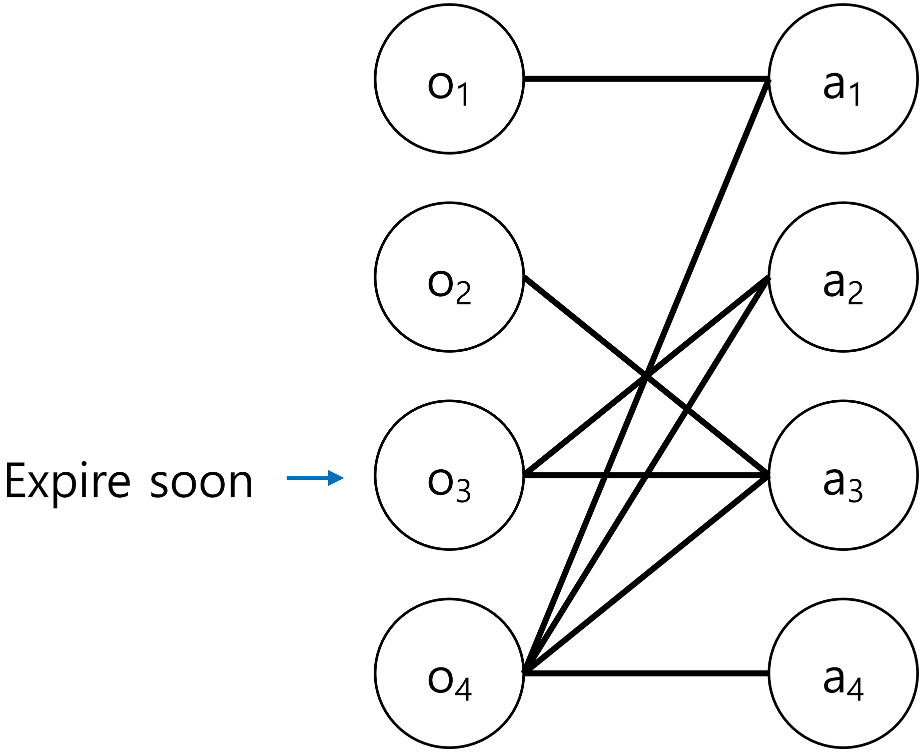
Authentication Design

- Match vertices: fewer edges first



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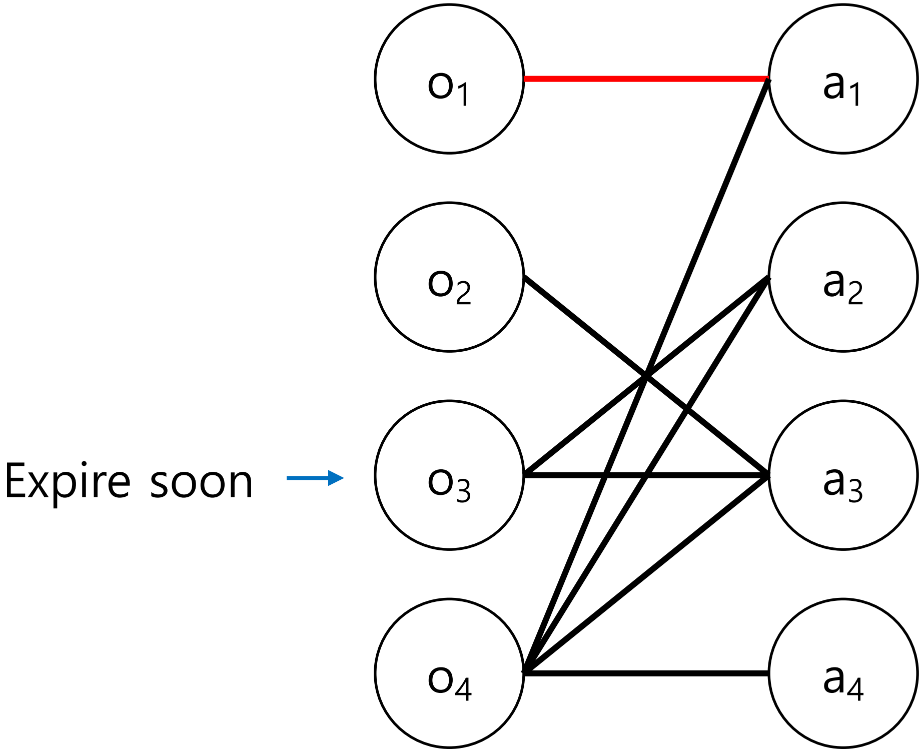

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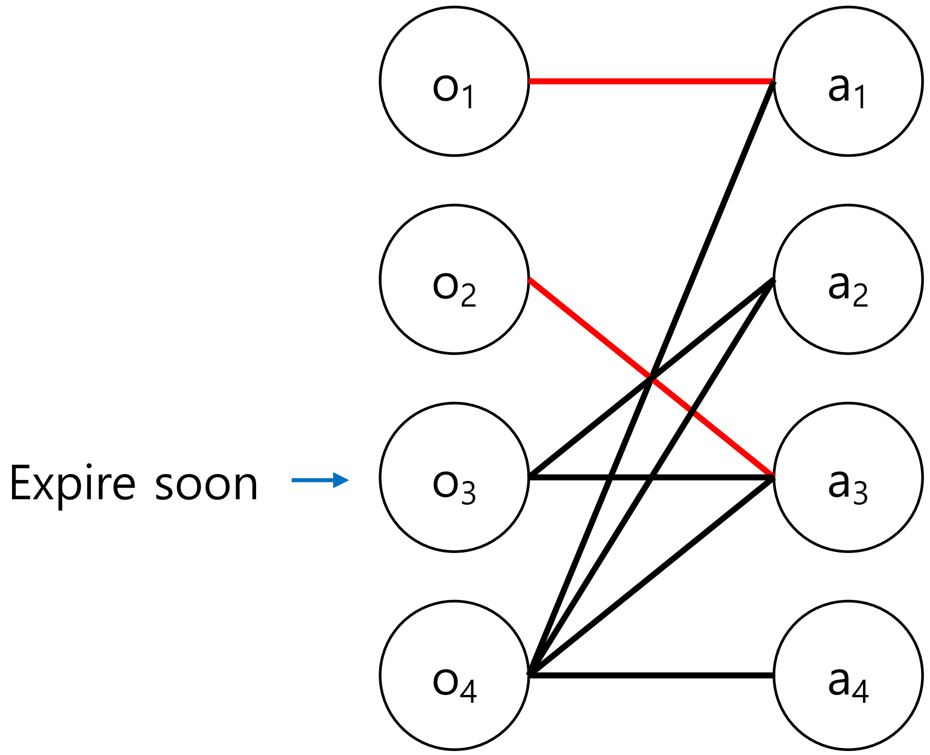
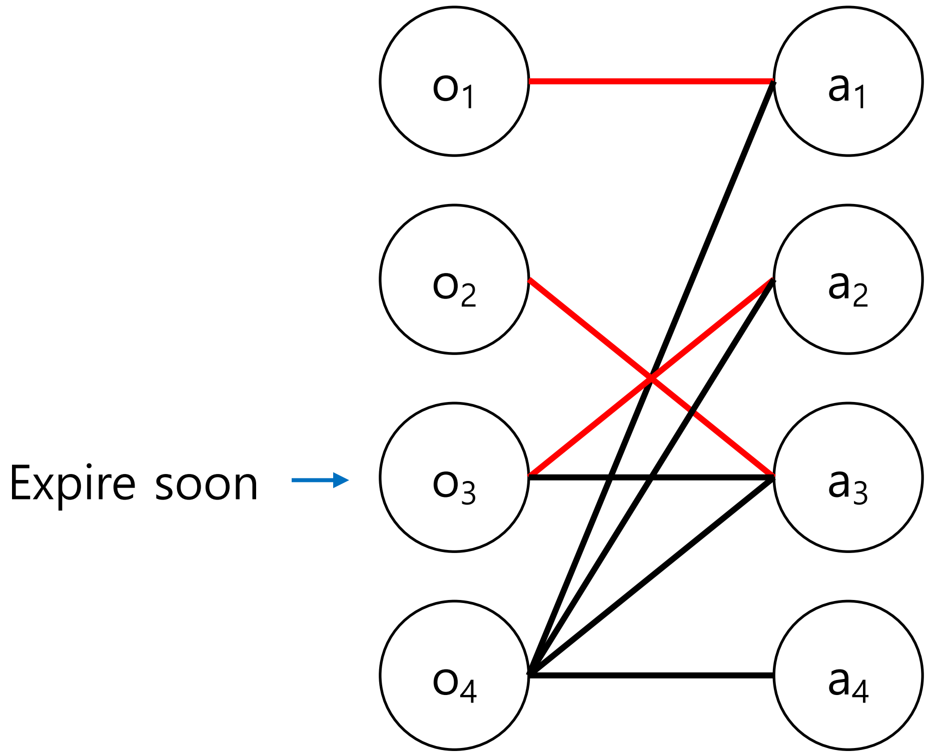


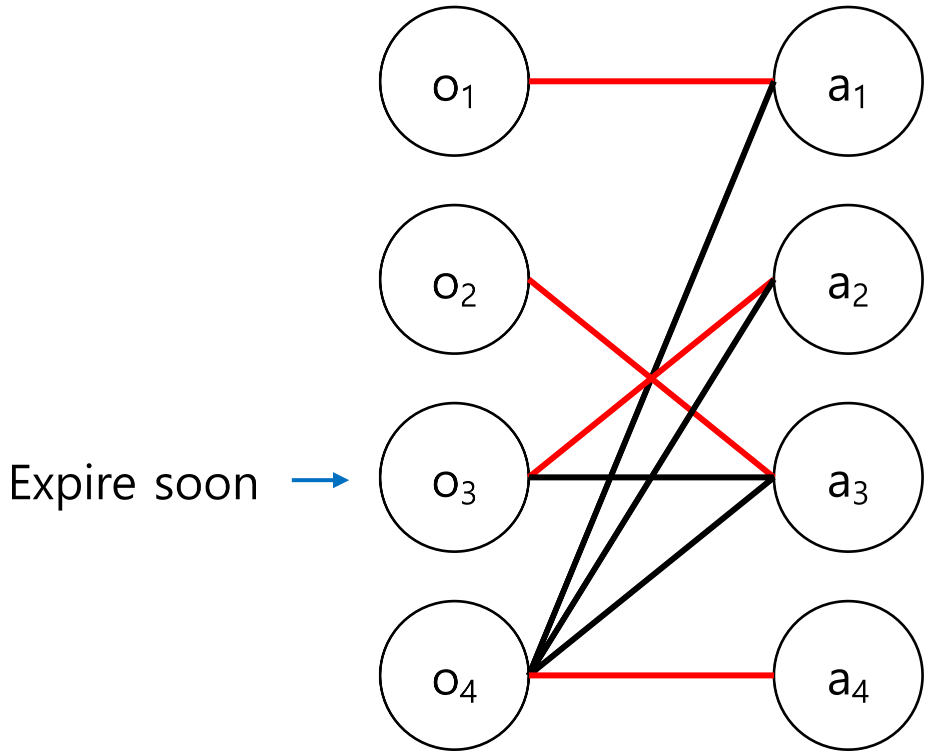
Authentication Design

- Match vertices: fewer edges first



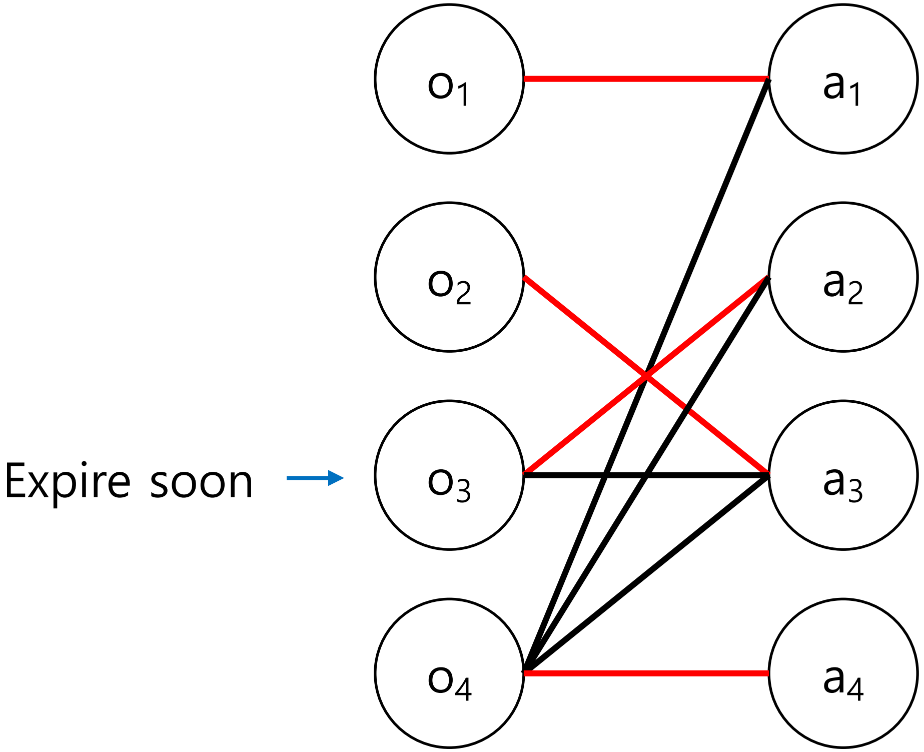
Authentication Design

- Match vertices: fewer edges first



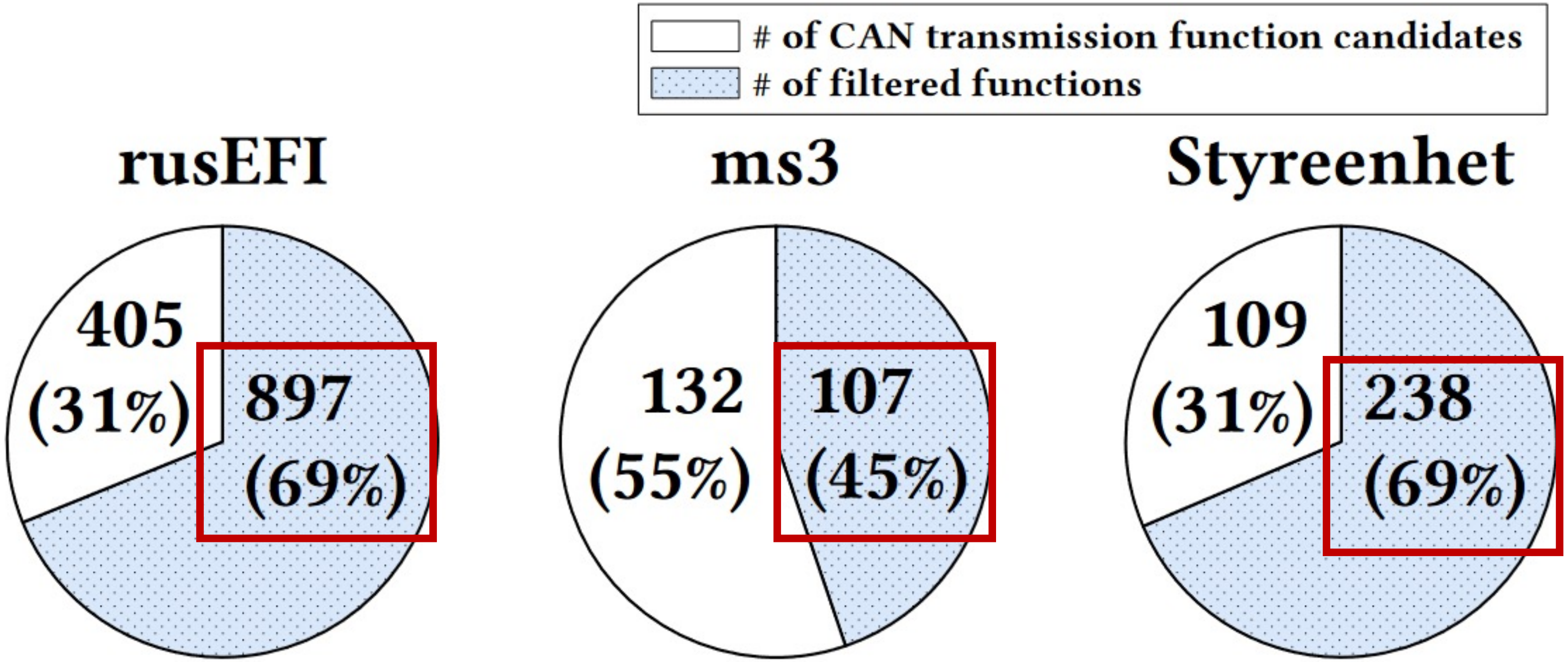
Authentication Design

- Match vertices: fewer edges first

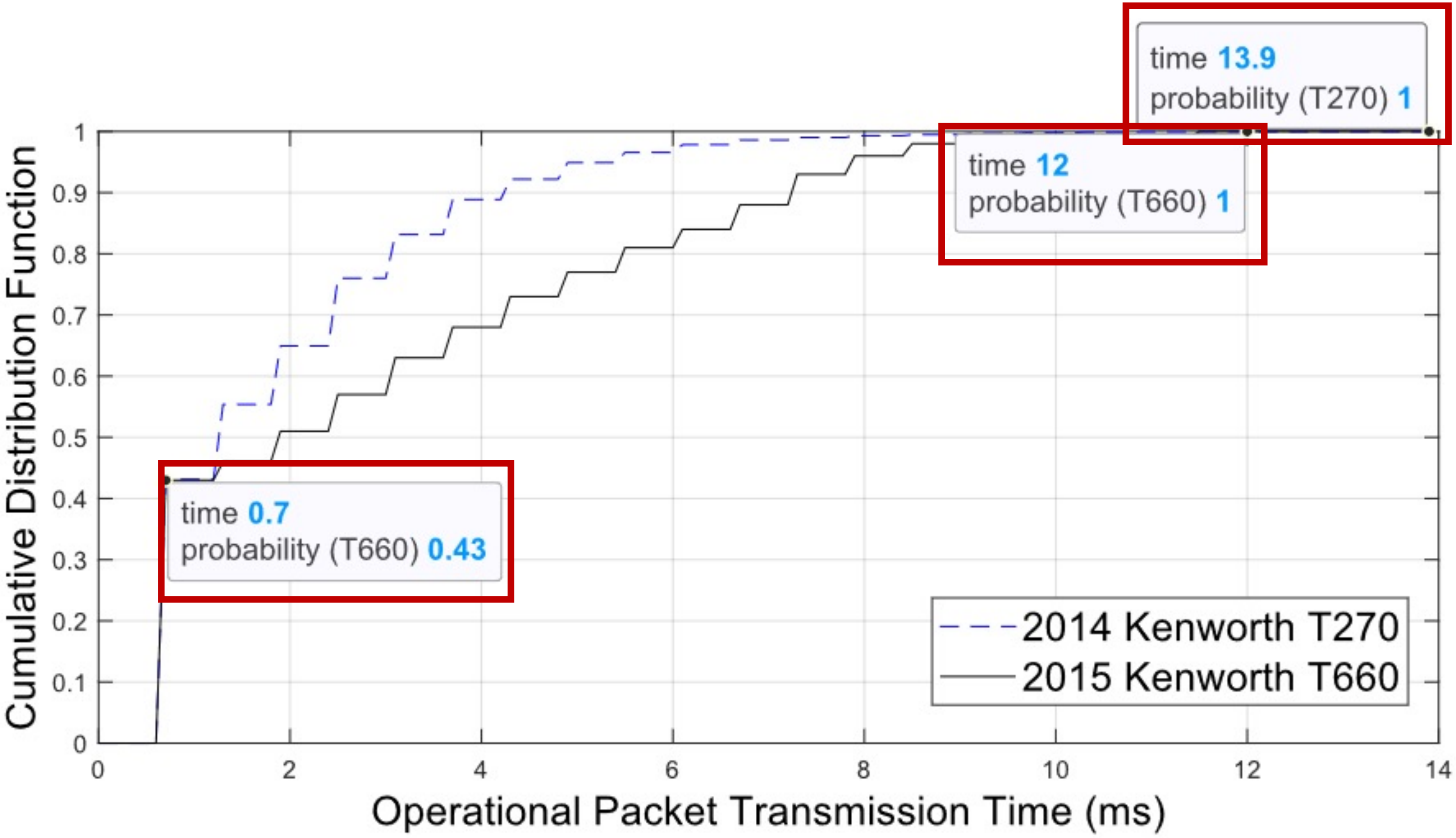


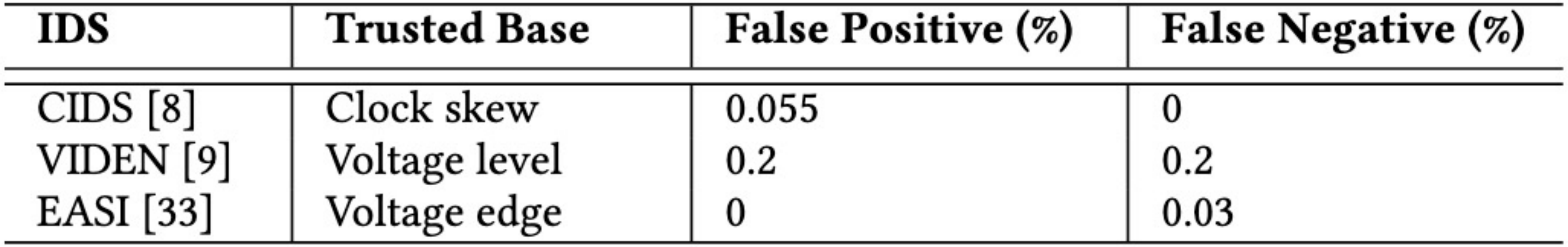
Match = # of auth packets
Authentic!

Evaluation: Static Analysis Efficiency



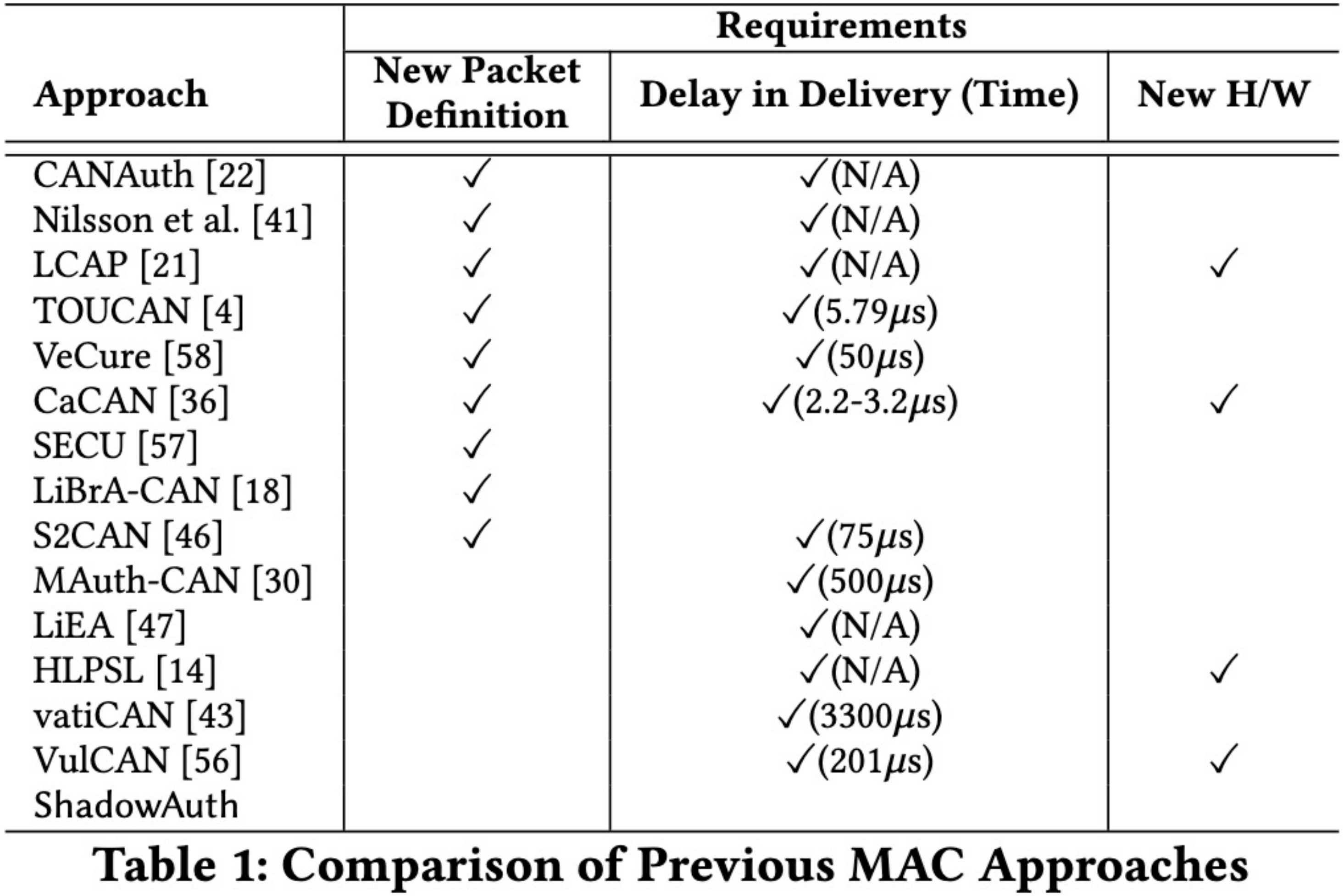
Evaluation: Asynchronous Delay





IDS	Trusted Base	False Positive (%)	False Negative (%)
CIDS [8]	Clock skew	0.055	0
VIDEN [9]	Voltage level	0.2	0.2
EASI [33]	Voltage edge	0	0.03

Table 3: Attack Detection Comparison with IDSs



Approach	Requirements		
	New Packet Definition	Delay in Delivery (Time)	New H/W
CANAuth [22]	✓	✓(N/A)	
Nilsson et al. [41]	✓	✓(N/A)	
LCAP [21]	✓	✓(N/A)	✓
TOUCAN [4]	✓	✓(5.79μs)	
VeCure [58]	✓	✓(50μs)	
CaCAN [36]	✓	✓(2.2-3.2μs)	✓
SECU [57]	✓		
LiBrA-CAN [18]	✓		
S2CAN [46]	✓	✓(75μs)	
MAuth-CAN [30]		✓(500μs)	
LiEA [47]		✓(N/A)	
HLPSL [14]		✓(N/A)	✓
vatiCAN [43]		✓(3300μs)	
VulCAN [56]		✓(201μs)	✓
ShadowAuth			

Table 1: Comparison of Previous MAC Approaches