CANSentry: Securing CAN-Based CPS against Denial and Spoofing Attacks

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Slides courtesy of Dr. Abdulmalik Humayed, Jazan University, Saudi Arabia

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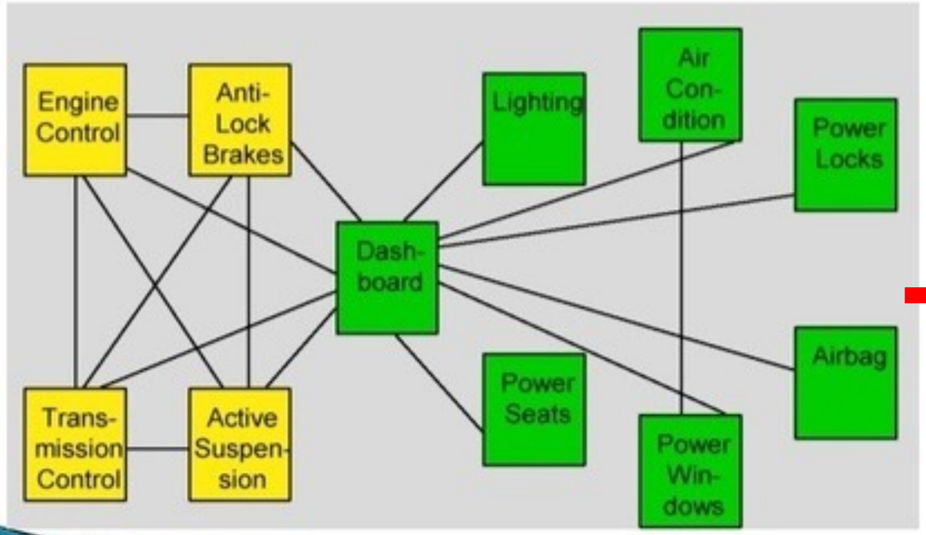
The Controller Area Network (CAN)

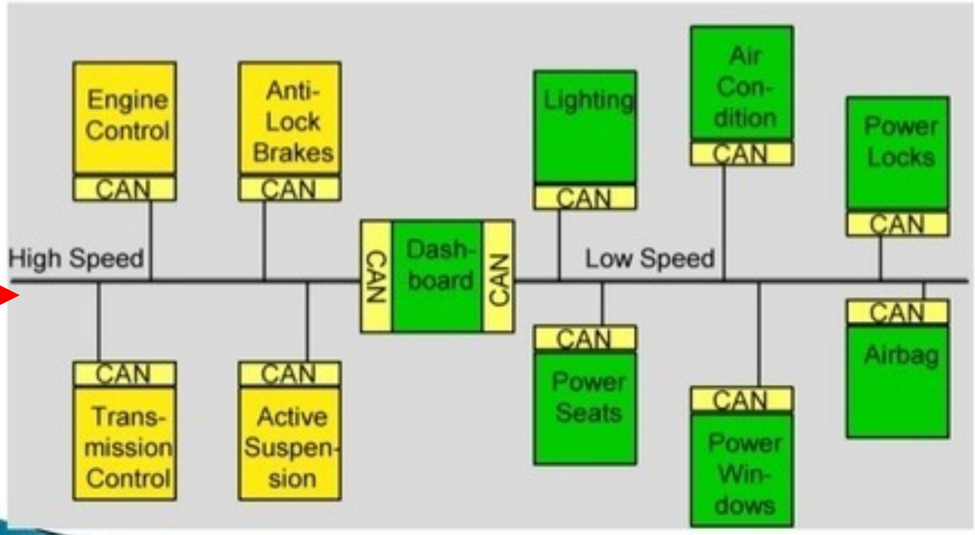
- The most common communication protocol for automotive and industrial applications
- On-Board Diagnostics (OBD-II) is mandated to be deployed in all cars for emission control with CAN only
- It allows data transmission in hostile environments
- Due to its bus topology, it greatly reduces vehicles’ cost and weight

The Controller Area Network (CAN)

Without CAN



With CAN



https://www.quora.com/Why-is-CAN-protocol-preferred-to-be-used-in-automotive-application

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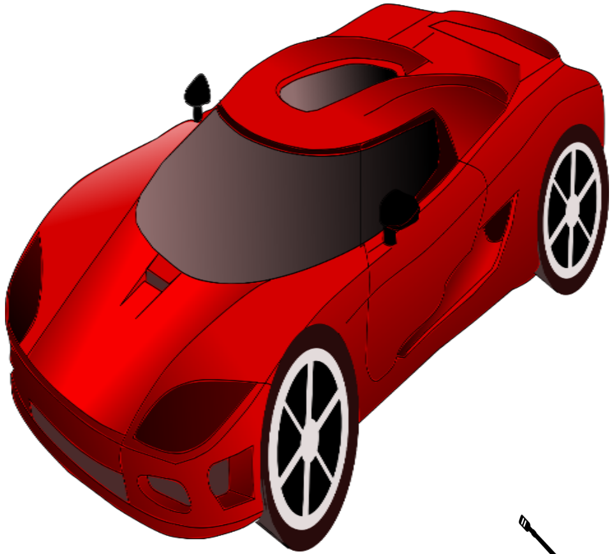

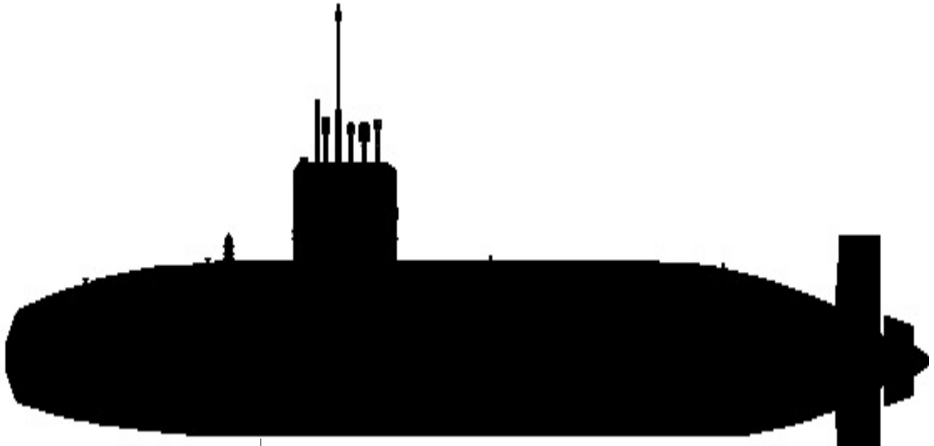

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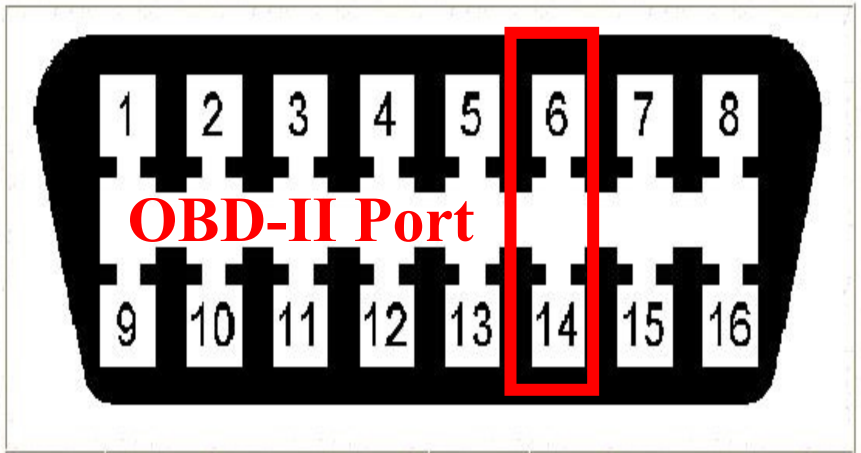
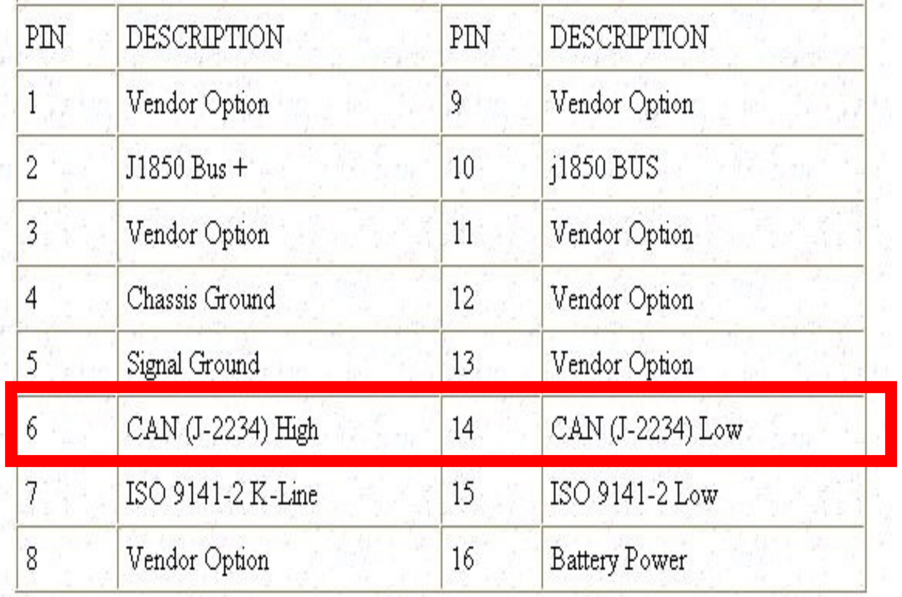
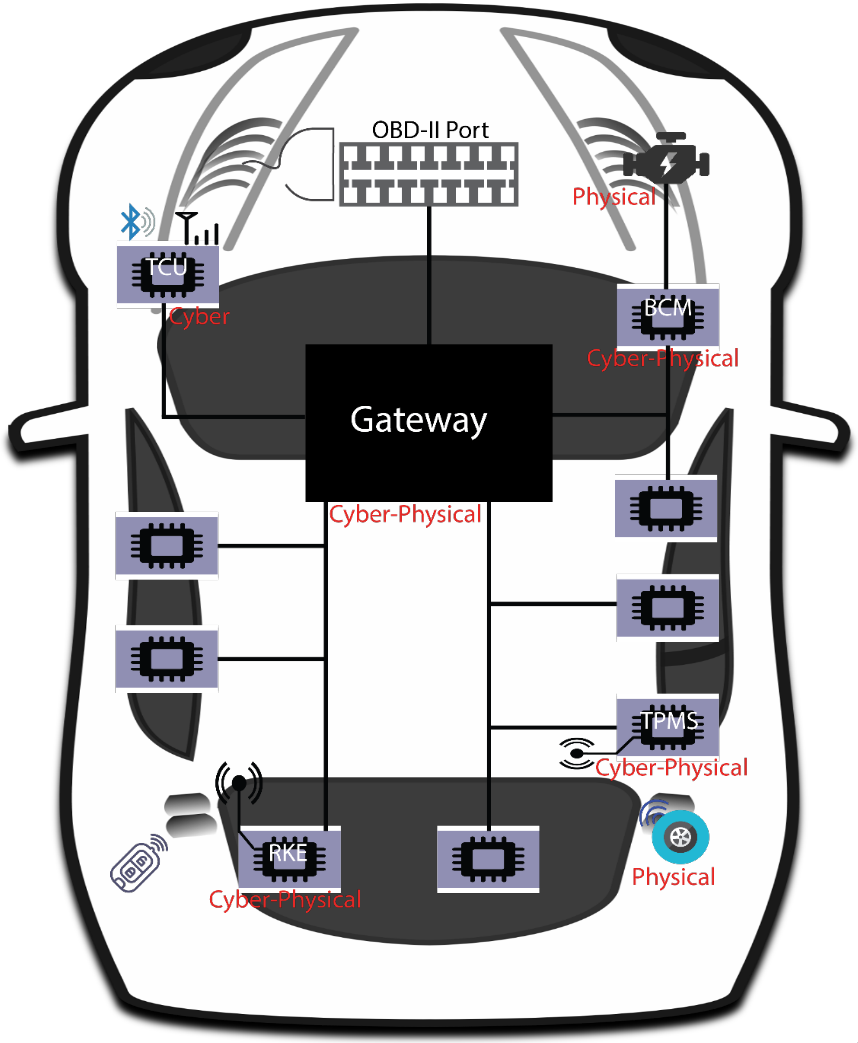




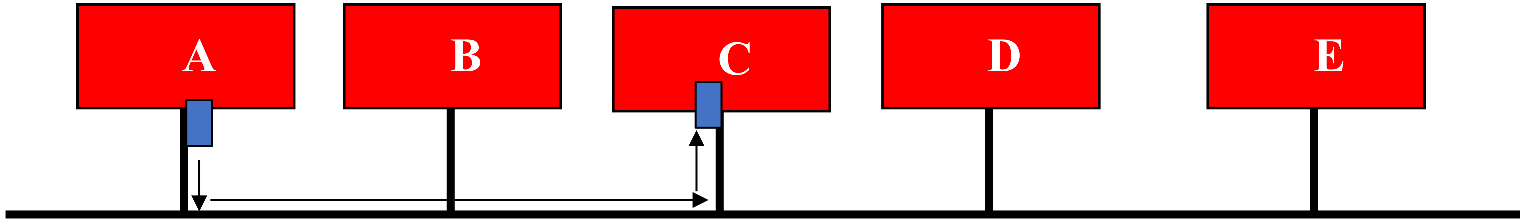
PIN	DESCRIPTION	PIN	DESCRIPTION
1	Vendor Option	9	Vendor Option
2	J1850 Bus +	10	j1850 BUS
3	Vendor Option	11	Vendor Option
4	Chassis Ground	12	Vendor Option
5	Signal Ground	13	Vendor Option
6	CAN (J-2234) High	14	CAN (J-2234) Low
7	ISO 9141-2 K-Line	15	ISO 9141-2 Low
8	Vendor Option	16	Battery Power

OBD-II Connector and Pinout



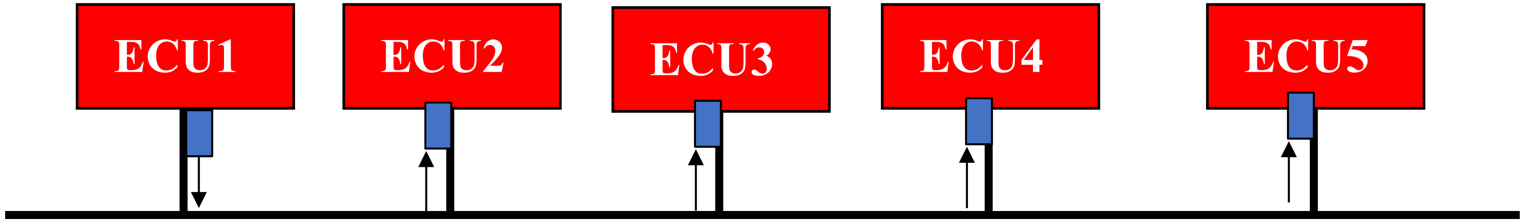
The Controller Area Network (CAN)

- Conventional peer-to-peer communication paradigm
  - Hey! I’m A, this is a message to C



Source: A	Dest: C	Message: Hello

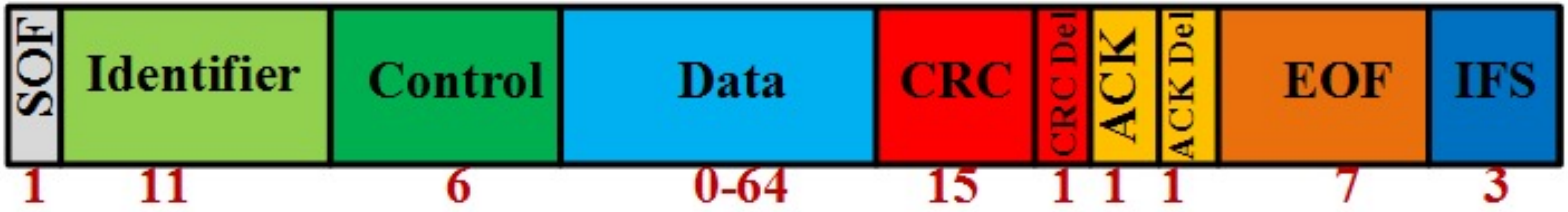
- In CAN
  - Hey! This is a message with ID 10 to everyone



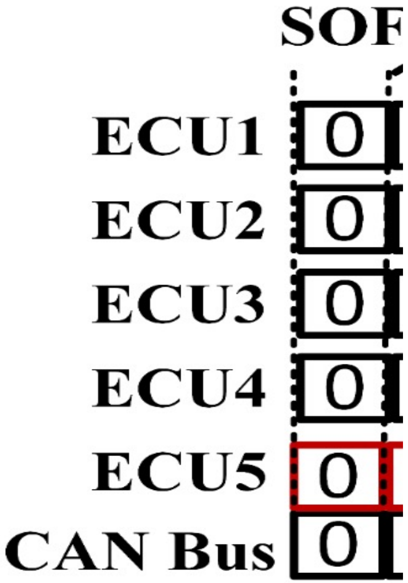
Message ID: 10	Message: Hello

CAN Frames & Arbitration

- Format of CAN frames
  - Each frame is identified by its arbitration ID
  - The frame with the lowest ID wins the arbitration and dominates the bus
  - Different types of frames use different ID
  - Ideally, IDs should be used uniquely across ECUs



CAN Frames & Arbitration



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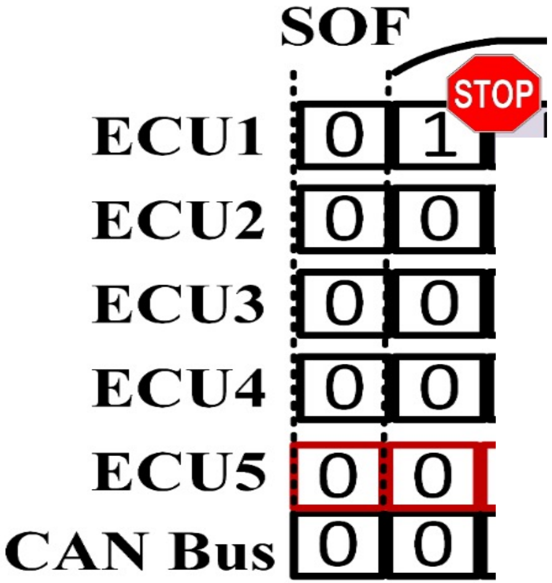

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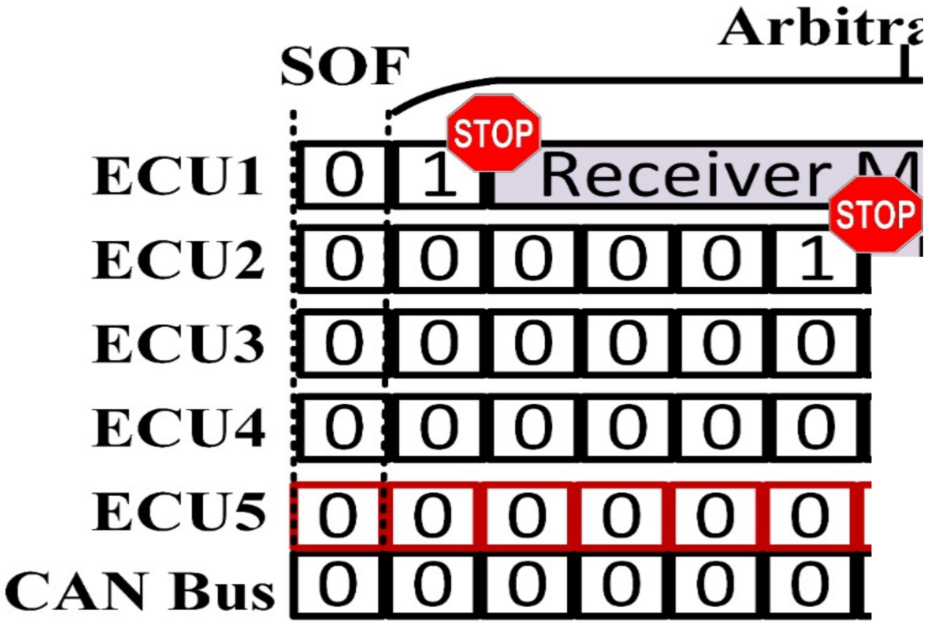
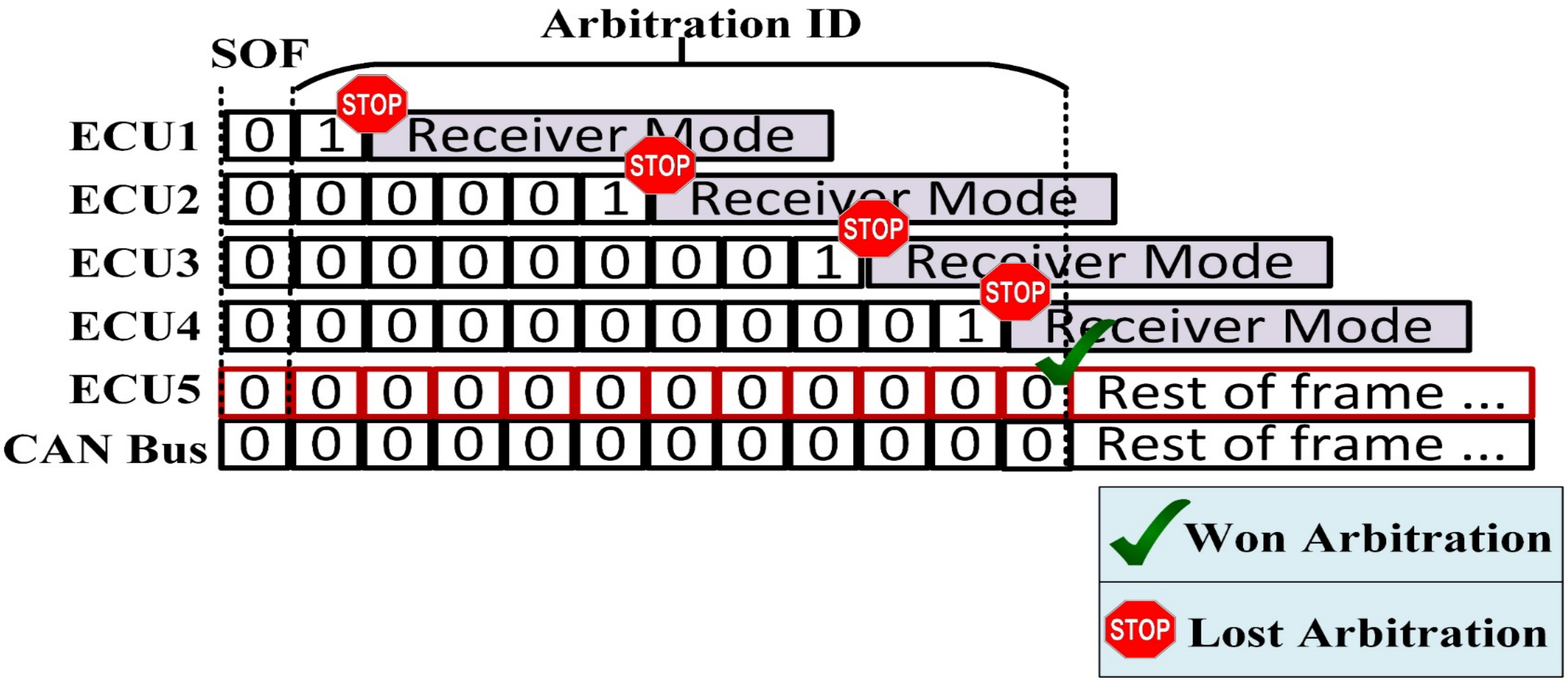


ECU1	0	1	Receiver M			
ECU2	0	0	0	0	0	1
ECU3	0	0	0	0	0	0
ECU4	0	0	0	0	0	0
ECU5	0	0	0	0	0	0
CAN Bus	0	0	0	0	0	0

CAN Frames & Arbitration



	SOF	Arbitration ID											
ECU1	0	1	Receiver Mode										
ECU2	0	0	0	0	0	1	Receiver Mode						
ECU3	0	0	0	0	0	0	0	0	1	Receiver Mode			
ECU4	0	0	0	0	0	0	0	0	0	0	1	Receiver Mode	
ECU5	0	0	0	0	0	0	0	0	0	0	0	0	Rest of frame …
CAN Bus	0	0	0	0	0	0	0	0	0	0	0	0	Rest of frame …

✓ Won Arbitration

STOP Lost Arbitration

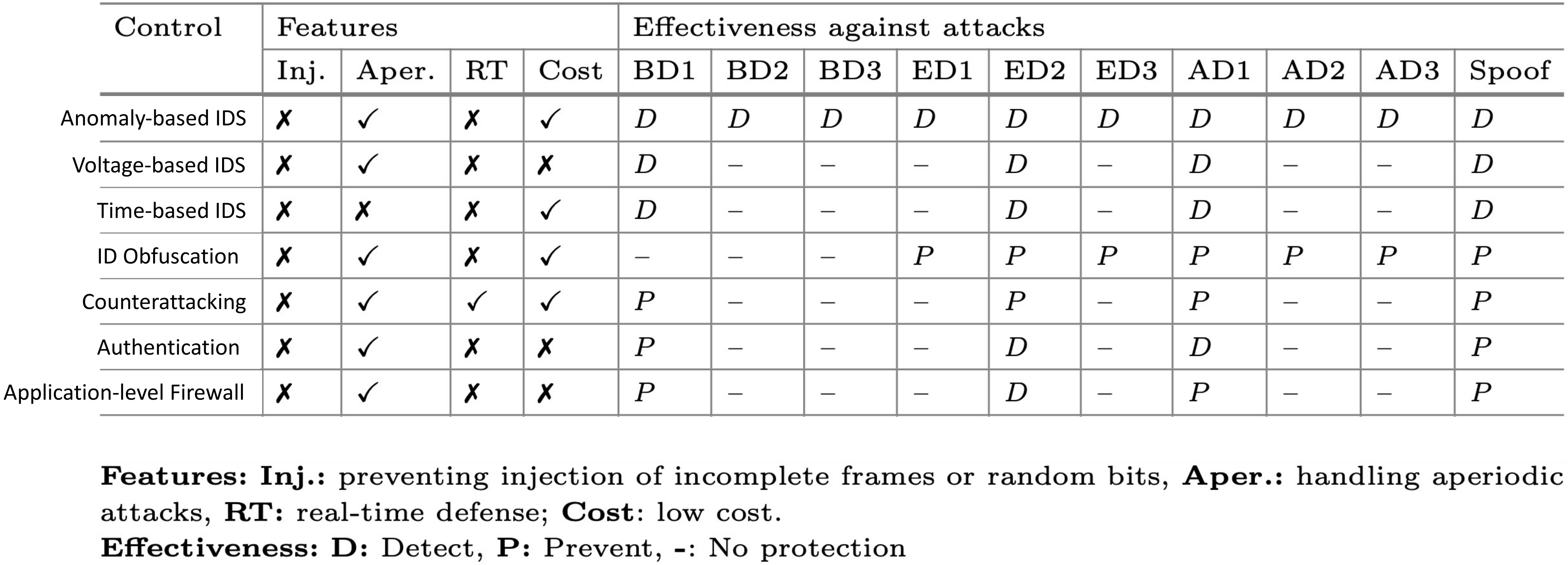
Existing Attacks

- **Denial attacks**
  [S&P’10, CCS’16, DIMVA’17, ARES’17, ESORICS’17]
  - Bus Denial (BD): 0x0 ID, dominant bits via Test Mode exploitation or custom ECU
  - ECU Denial (ED) : CAN Controller abuse or bypass & Error Handling abuse
  - Arbitration (AD) : injection of high priority IDs, dominant bit, or fake partial frames
- **Spoofing attacks**
  [S&P’10, DefCon’13, arXiv preprint’19, BlackHat’15]
  - An attacker sends any CAN ID of her choice to spoof other ECUs
  - ECUs could be compromised through a remote channel, and CAN frames are sent to unlock doors, stall the engine, or control the steering wheel

Existing Controls

- **Controls**
  - Node identification and IDS [USENIX Sec’16, CCS’17, CCS’18, TIFS’18, ACSAC’19]
  - CAN-ID Obfuscation [escar’15, SCAV’17, TODAES’17, Access’19]
  - Counterattacking [VTC’12, escar’14, SafeComp’18]
  - Authentication [DATE’09, DATE’13, ICCPS’13]
  - Firewalls [Micro’18]
- **Problems with existing controls**
  - Many require major software & hardware modifications
  - Changes to the protocol may require ALL ECUs to be updated
  - May introduce overheads for key management and crypto operations
  - Cannot defend against abused or compromised CAN controllers
  - None can handle attacks based on incomplete frames

Existing Controls



Control	Features				Effectiveness against attacks									
	Inj.	Aper.	RT	Cost	BD1	BD2	BD3	ED1	ED2	ED3	AD1	AD2	AD3	Spoof
Anomaly-based IDS	✗	✓	✗	✓	*D*	*D*	*D*	*D*	*D*	*D*	*D*	*D*	*D*	*D*
Voltage-based IDS	✗	✓	✗	✗	*D*	–	–	–	*D*	–	*D*	–	–	*D*
Time-based IDS	✗	✗	✗	✓	*D*	–	–	–	*D*	–	*D*	–	–	*D*
ID Obfuscation	✗	✓	✗	✓	–	–	–	*P*	*P*	*P*	*P*	*P*	*P*	*P*
Counterattacking	✗	✓	✓	✓	*P*	–	–	–	*P*	–	*P*	–	–	*P*
Authentication	✗	✓	✗	✗	*P*	–	–	–	*D*	–	*D*	–	–	*P*
Application-level Firewall	✗	✓	✗	✗	*P*	–	–	–	*D*	–	*P*	–	–	*P*

Features: Inj.: preventing injection of incomplete frames or random bits, **Aper.:** handling aperiodic attacks, **RT:** real-time defense; **Cost**: low cost.
Effectiveness: D: Detect, **P:** Prevent, **-**: No protection

Threat Model

- Attackers have remote access (via wireless access points) or brief physical access (via OBD-II port) to the CAN bus
- **The CAN Abuser**
  - Has complete control over ECU's software but not hardware
  - Abuse arbitration and error handling mechanisms to achieve malicious goals
- **The Skipper**
  - Skips CAN controller to directly access CAN bus
    - Uses a custom MCU directly connected to the bus
    - Manipulate CAN controller's GPIO pins to directly access to the bus
  - Attacker does not comply with CAN standards

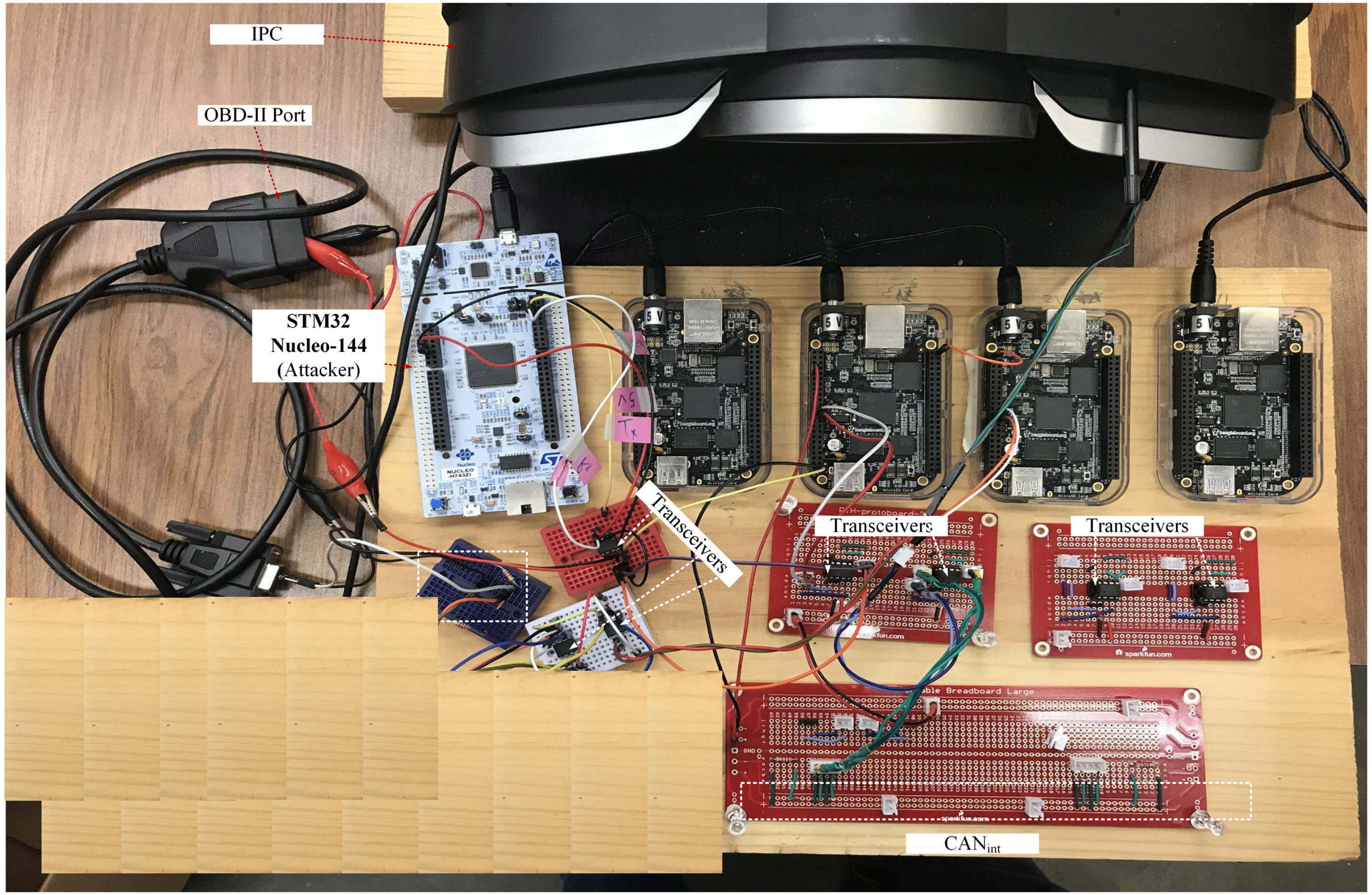
Threat Model

- **Denial attacks**: disable certain functionalities in a target ECU or bus
  - ECU is shutdown (bus-off state)
  - Bus is occupied
  - Specific CAN ID cannot win arbitration
- **Spoofing attacks**: transmit an ID belonging to another ECU
  - Receiving ECUs are spoofed resulting in:
    - Disabling brakes
    - Taking control of the steering wheel
    - False data injection

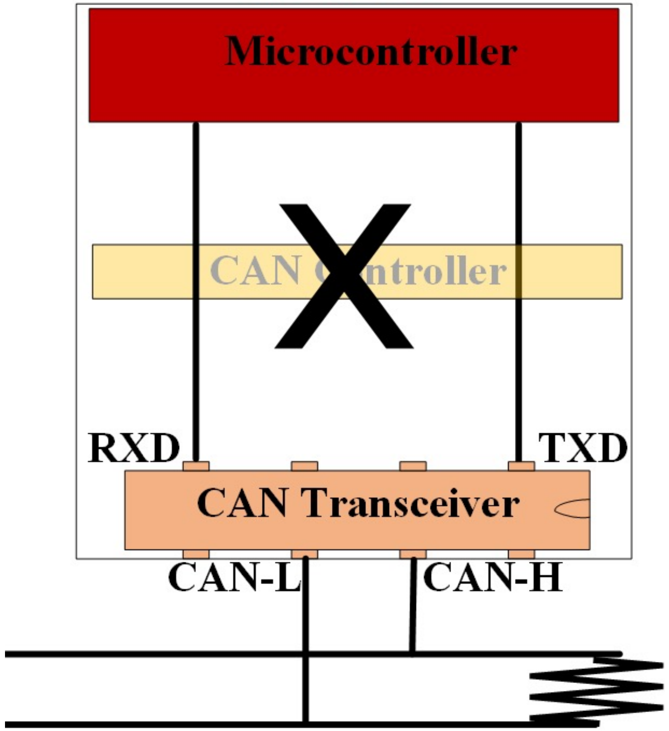
A Novel Stealthy Arbitration Denial Attack

- New objectives: Selective, Stealthy, & Practical
- Overview of the attack
  - Passively monitors the bus to detect a targeted ID in the arbitration phase
  - Overwrites the last recessive bit in the target ID to win arbitration
  - Completes the transmission with a fake frame
- Challenges
  - Existing tools only deal with complete CAN frames
  - High degree of precision is needed
  - Unexpected delays, premature injection, or malformed frames may cause incomplete frames resulting in bus errors

A Novel Stealthy Arbitration Denial Attack

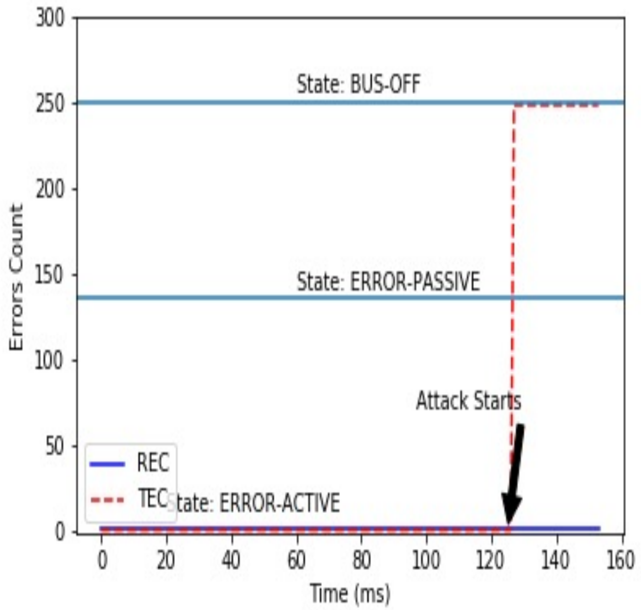


The Skipper

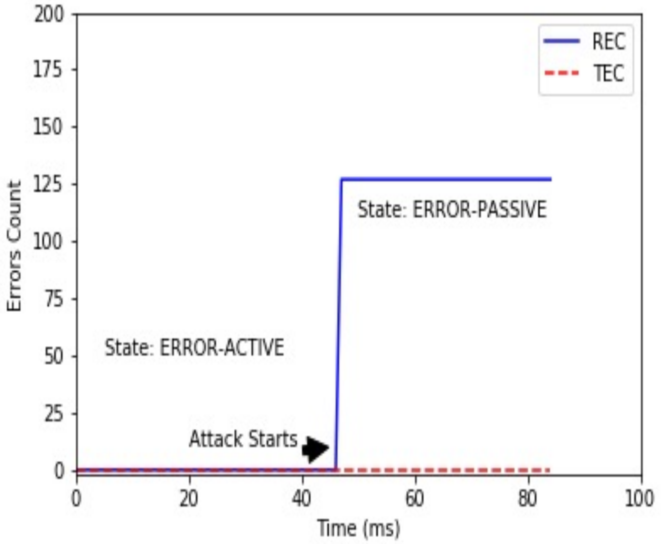


A Novel Stealthy Arbitration Denial Attack

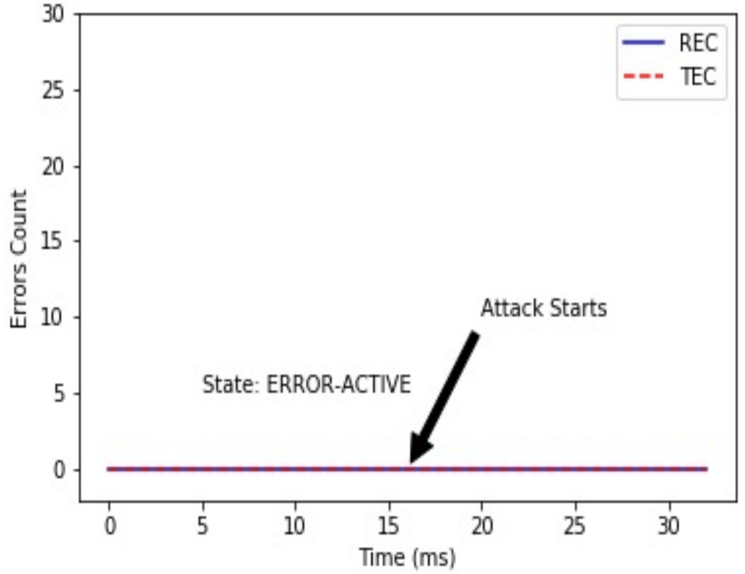
- Stealthy - the new attack does not incur any error
- Selective - the new attack only affects the targeted ECU or CAN ID



ECU Denial (ED)



Arbitration Denial 2 (AD2)

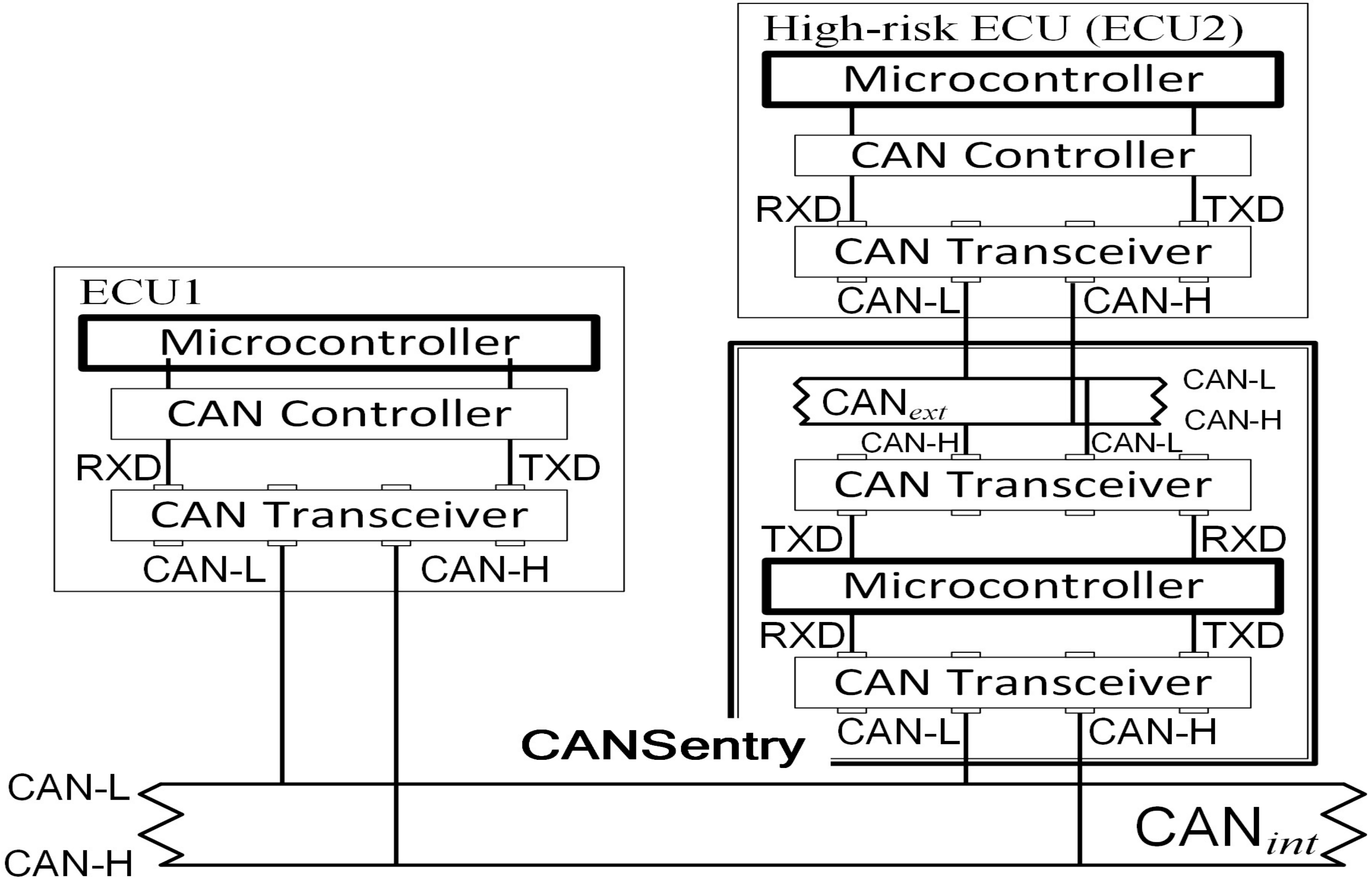


Arbitration Denial 3 (AD3)

CANSentry: Overview

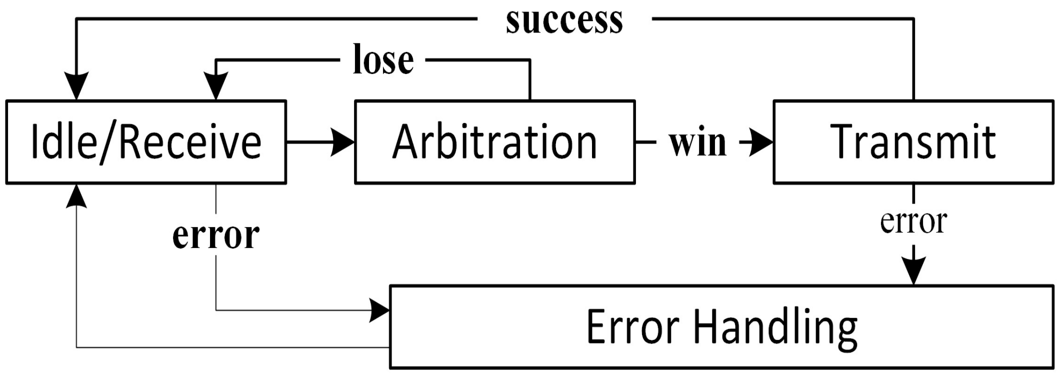
- A novel firewall sitting between any high-risk ECU and the bus
  - High-risk ECU: an ECU with remote access (entertainment system, Bluetooth) or open hardware access (OBD-II)
- Monitors incoming traffic from the ECU
- Ensures the consistency between the CAN Bus state and the ECU state
  - E.g., when another ECU wins arbitration and transmits data, the protected ECU could only receive. It cannot interrupt the BUS traffic.
- Uses firewall rules to block illegal traffic
- Low-cost and highly efficient implementation

CANSentry: Architecture

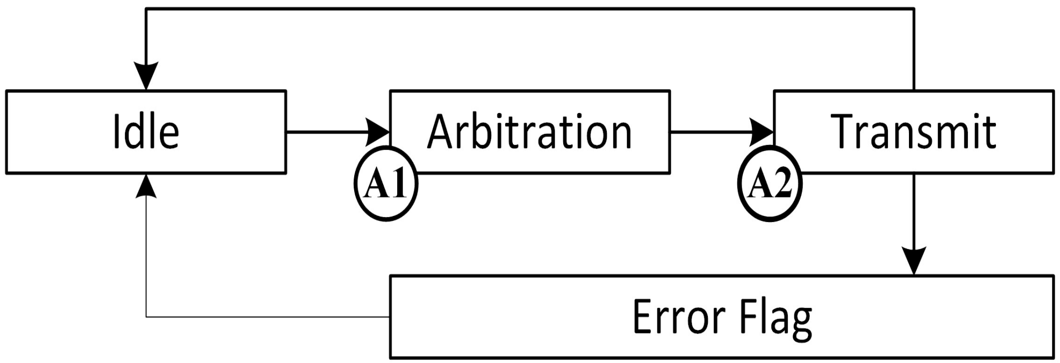


CANSentry: States

- States and states transitions of CAN bus and nodes



States of a CAN Node



States of the CAN Bus

CANSentry: State Transition Rules

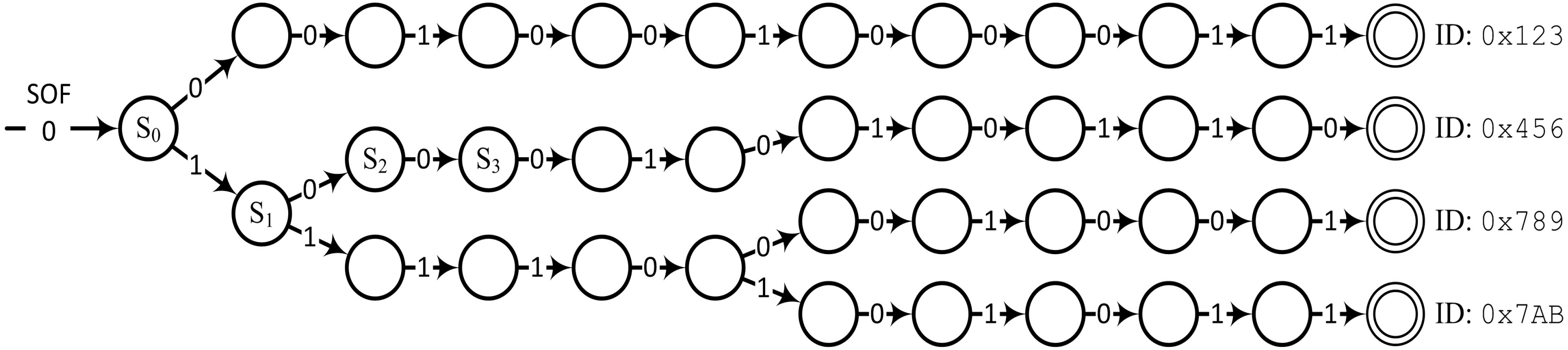
- **Main principle**: The fundamental principle of the firewall is to ensure that at any time high-risk nodes on the external bus operate in a state consistent with the state of the internal bus.

CAN_{INT} State	Consistent State in CAN_{EXT}
IDLE	IDLE/RECIEVE, ARBITRATION, and TRANSMIT
ARBITRATION	IDLE/RECIEVE and ARBITRATION
TRANSMIT or ERROR FLAG	IDLE/RECEIVE

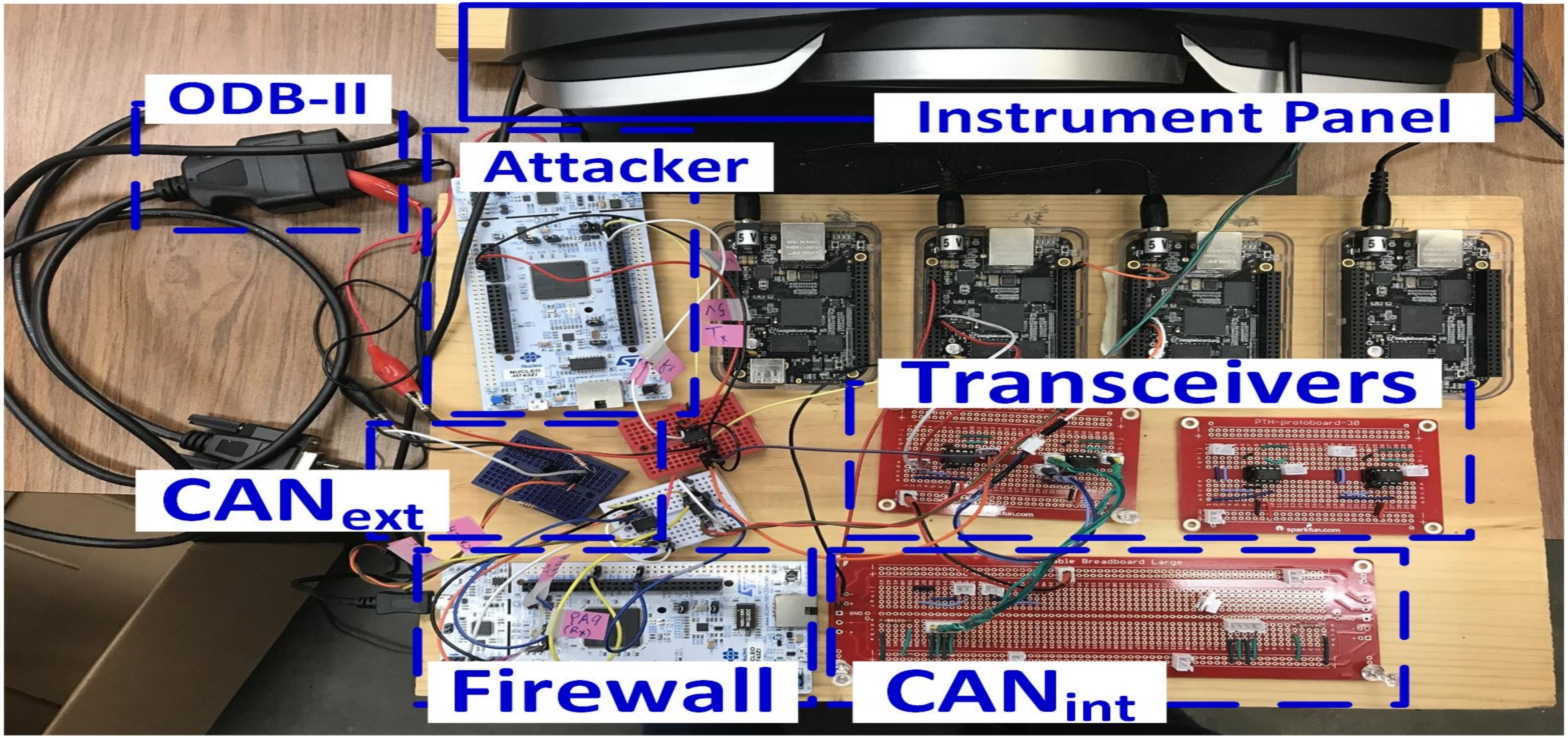
Example: ***R_1***: When the internal bus is in either $\text{TRANSMIT}_{\text{int}}$ or ERRORFLAG state, the firewall always forwards the traffic from CAN_{int} to CAN_{ext} and blocks the traffic from external to internal, regardless of high-risk node's state.

CANSentry: CAN ID filtering in arbitration

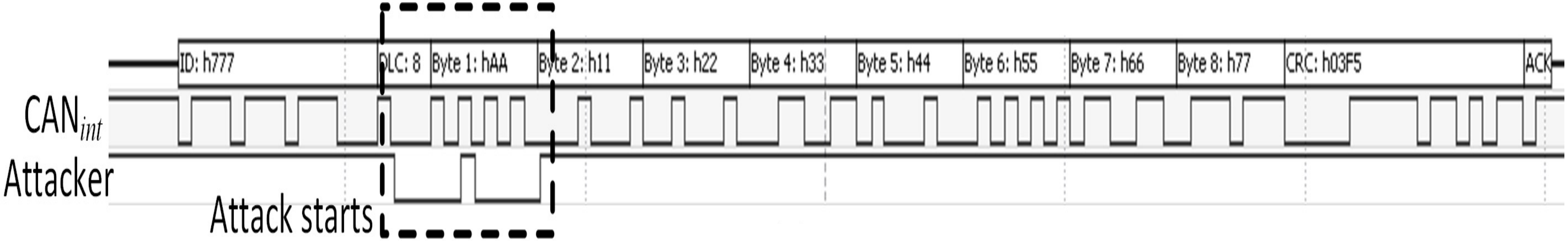
- When the internal bus is in ARBITRATION state, the firewall forwards traffic that has a CAN ID in the **arbitration whitelist** and conforms to CAN specifications from CAN$_{ext}$ to CAN$_{int}$.
- Prevent spoofing attacks
- Uses automata for efficient CAN ID matching
  - Example: this automata allows four CAN IDs: 0x123, 0x456, 0x789, 0x7AB



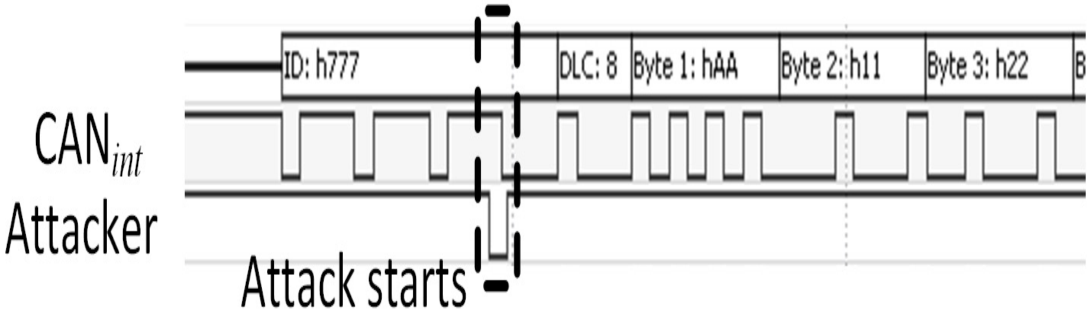
CANSentry: Implementation



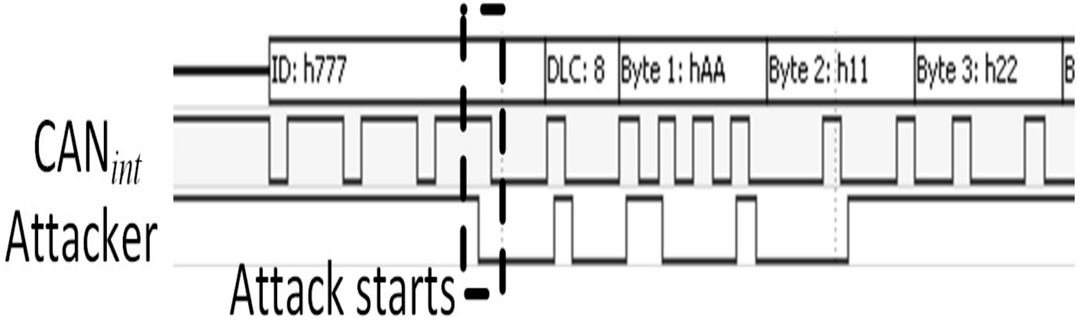
CANSentry: Evaluation



Bus-Off Attack



Arbitration Denial Attack

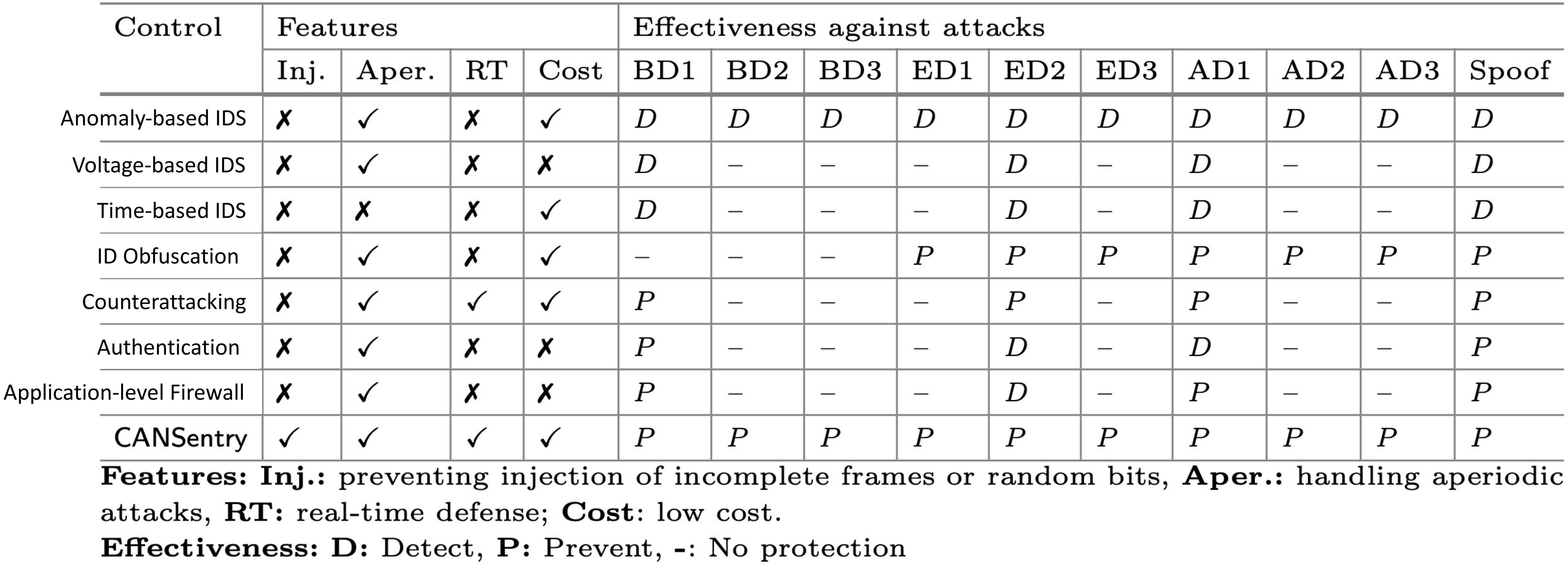


Stealthy Arbitration Denial Attack

Security Analysis

- CANSentry nodes are deployed in a physically secure environment
  - Makes it difficult for an adversary to bypass or alter
- CANSentry only has two network interfaces - CAN_{ext} and CAN_{int}
  - The limited communication channel and the simplicity of CAN makes it impractical to compromise the operations of the firewall from CAN_{ext}.
- The simplicity of the firewall makes it unlikely to have significant software faults

Security Analysis



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Time-based IDS	✗	✗	✗	✓	*D*	–	–	–	*D*	–	*D*	–	–	*D*
ID Obfuscation	✗	✓	✗	✓	–	–	–	*P*	*P*	*P*	*P*	*P*	*P*	*P*
Counterattacking	✗	✓	✓	✓	*P*	–	–	–	*P*	–	*P*	–	–	*P*
Authentication	✗	✓	✗	✗	*P*	–	–	–	*D*	–	*D*	–	–	*P*
Application-level Firewall	✗	✓	✗	✗	*P*	–	–	–	*D*	–	*P*	–	–	*P*
CANSentry	✓	✓	✓	✓	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*

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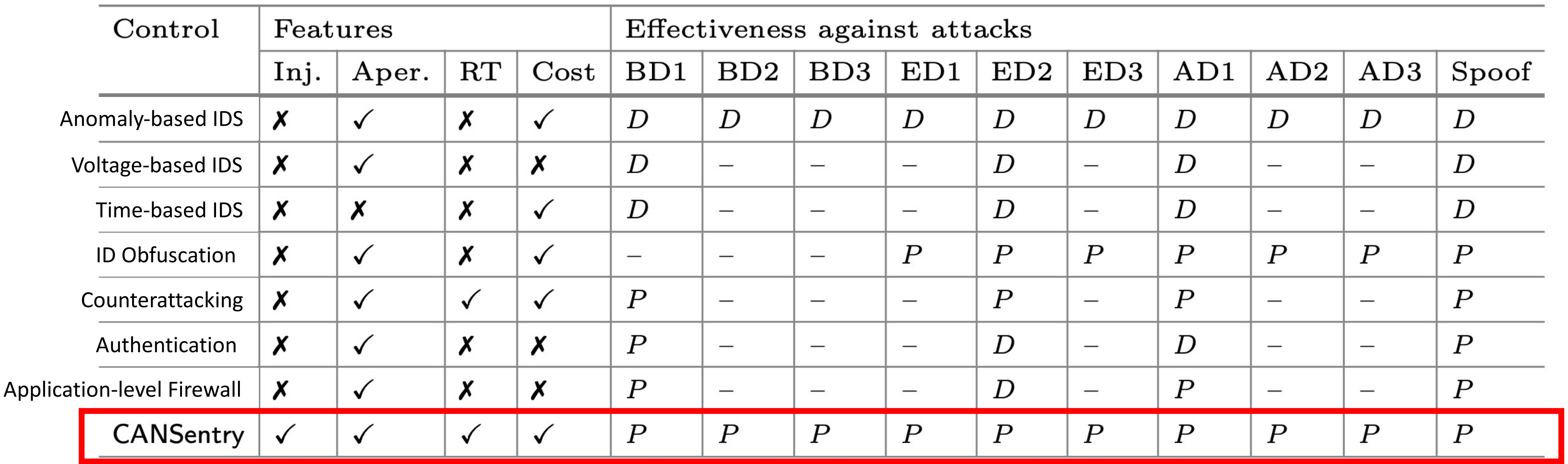

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CANSentry	✓	✓	✓	✓	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*	*P*

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Conclusions

- We summarized existing DoS and spoofing attacks on CAN
- We proposed and implemented a novel stealthy selective arbitration DoS attack
- We designed a novel *CANSentry* firewall to defend against attacks that violate the CAN standard or abuse CAN's error-handling mechanism
  - *CANSentry* is the first solution that detects and prevents a broad spectrum of CAN denial and spoofing attacks
  - *CANSentry* does not introduce noticeable overhead or delay
  - It is very cost-effective

Acknowledgment

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