In-Vehicle Security

CPS and IoT Security

Alessandro Brighente

Master Degree in Cybersecurity
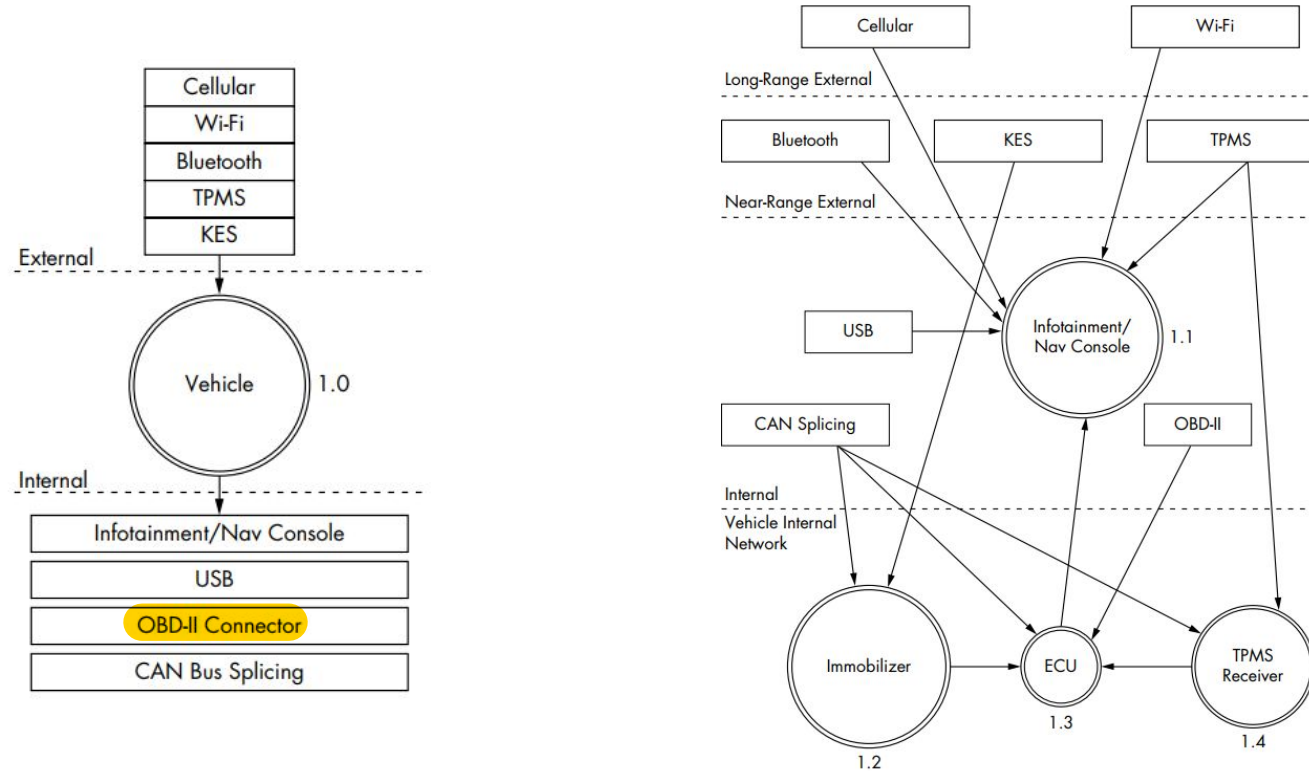
UNIVERSITÀ DEGLI STUDI DI PADOVA

SPRITZ SECURITY & PRIVACY RESEARCH GROUP

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Vehicle Components and Network

- Modern vehicles contain a large number of Electronic Control Units (ECUs)

- ECUs are embedded systems that control one or more (sub)system in a car or other vehicles

- Examples: engine control module, powertrain control module, transmission control module, suspension control module,...

- ECUs are nodes in a rather complex in-vehicle network, where they should communicate one another to report many different types of information

What is CAN Bus

- Controller Area Network (CAN) is an in-vehicle network bus-based standard developed in 1986 by Bosch

- It allows in-vehicle components (ECUs) to communicate one another

- It has broad application in automotive systems, including power train, suspension, and braking

- In 2003, it became a standard series with ISO 11898

- The Society of Automotive Engineers (SAE) standardized CAN bus communications to have asynchronous data rate up to 1 Mbps at a 40 m distance

Why CAN Bus

- **Robustness:** ideal for safety applications thanks to its durability and reliability (bit stuffing, bit monitoring, frame check, ack and CRC checks)

- **Low cost:** objective is to reduce errors, weight, wiring and costs

- **Flexibility:** it is a message-based protocol, so nodes can be added or removed without updating the system

- **Efficiency:** messages with high priority are clearly marked and have prioritized access to the bus

- To achieve reliability, it is important to prevent message collision such that no data gets lost

- Thanks to the shared bus and the message handling system, CAN allows for a reduced number of wires to achieve reliability

- Redundancy is the best way to achieve reliability, however it comes with a higher communication implementation cost (huge number of wires)

- Point-to-point communications were used before CAN
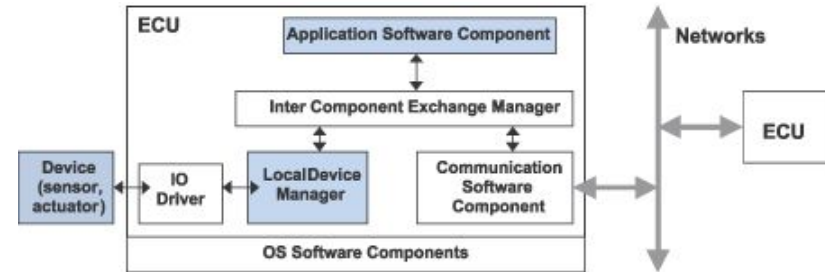
CAN Bus Architecture
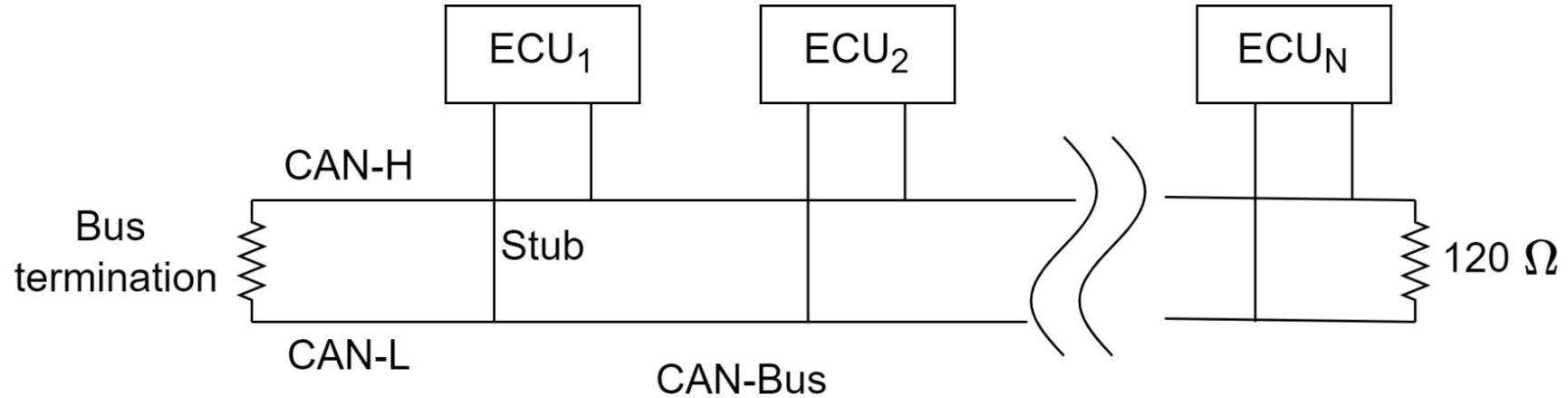
Electronic Control Unit

ECU Architecture

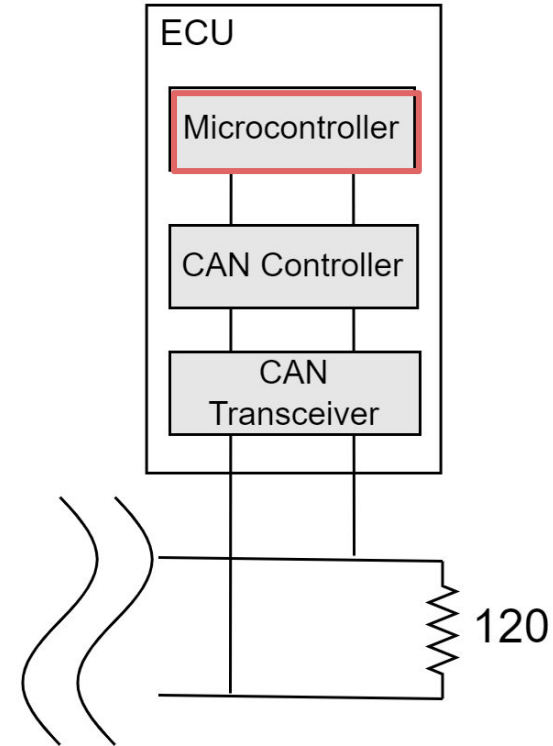SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Microcontroller:

- central processing unit of the ECU to decide what the received signal means and what messages it wants to transmit
- Allows for the connection of other devices, such as <u>sensors</u> and <u>actuators</u>

```
ECU
 ┌─────────────────┐
 │  Microcontroller │
 └─────────────────┘
 ┌─────────────────┐
 │  CAN Controller  │
 └─────────────────┘
 ┌─────────────────┐
 │      CAN         │
 │   Transceiver    │
 └─────────────────┘
```

120

**CAN controller:**

- Stores the received serial bits
  and passes messages to the
  processor
- Transmits bits serially on the bus
  upon reception from the
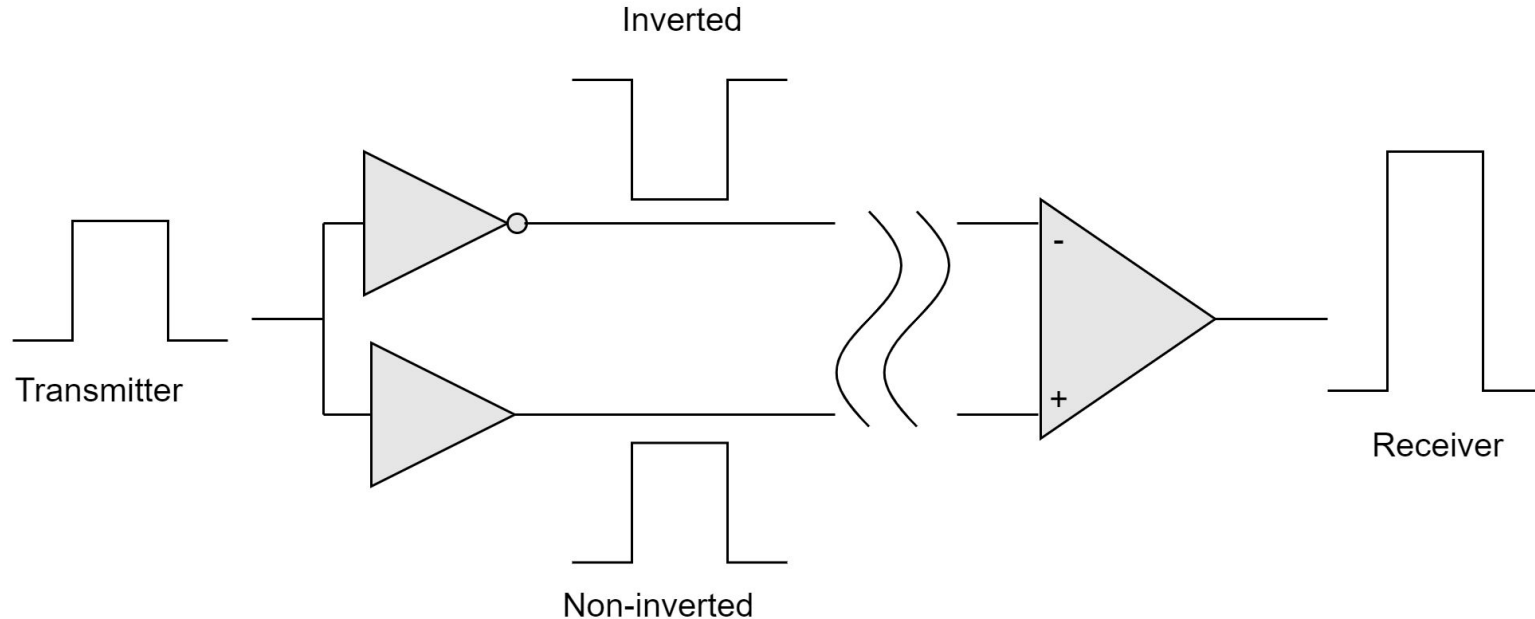  processor
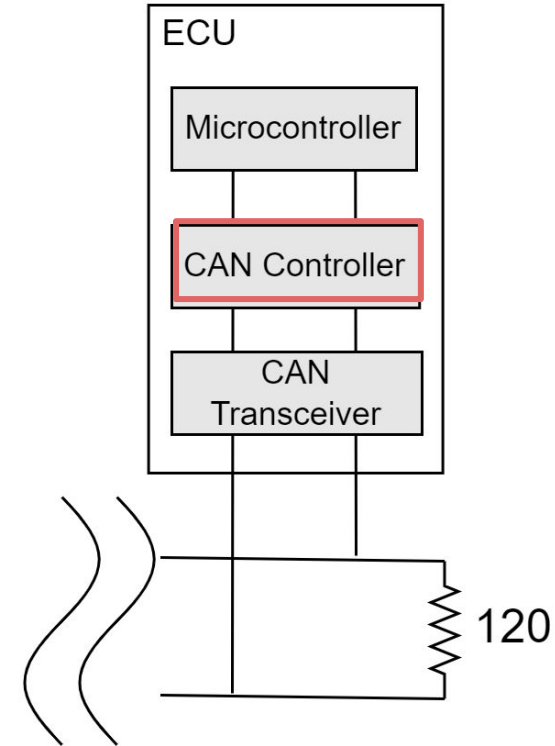
**CAN transceiver:**

- Protects the CAN controller from overvoltage

- Converts CAN bus levels to levels that the CAN controller can use

- Converts the data stream from the CAN controller to CAN bus levels
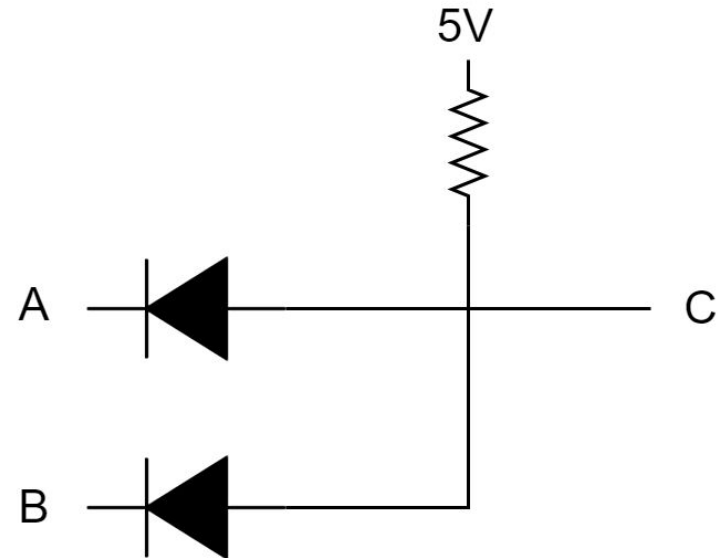
# CAN Bus Communication
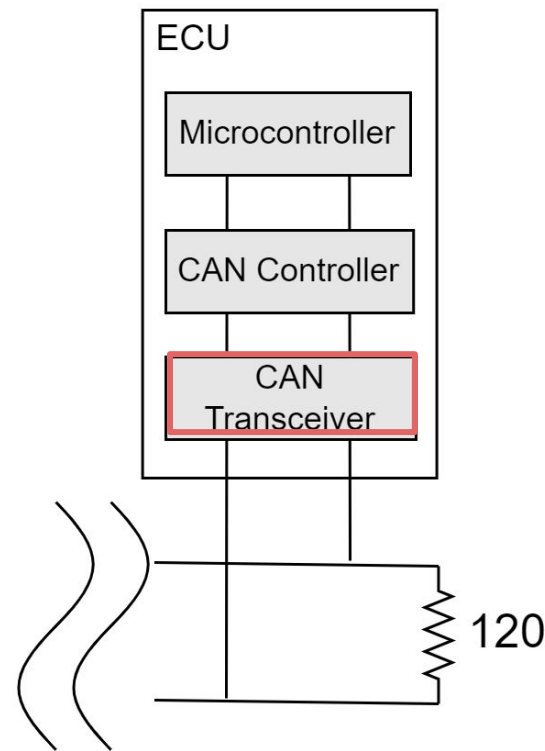
- CAN bus uses **differential wired-AND signals**

- It uses two signals, CAN high (CAN-H) and CAN low (CAN-L)

- They are either driven to a dominant state with CAN-H > CAN-L

- Or driven to a recessive state, with CAN-H $\leq$ CAN-L

- Dominant state = 0 bit

- Recessive state = 1 bit

# CAN Bus Communication

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

- CAN bus uses **differential** wired-AND signals

# CAN Bus Communication

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

- CAN bus uses differential **wired-AND signals**

| Input | | Output |
|---|---|---|
| **A** | **B** | **A AND B** |
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

- Either dominant or recessive

# CAN Bus Communication

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

- Dominant state = 0 bit

- Recessive state = 1 bit

# Physical and Data Link Layer

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA
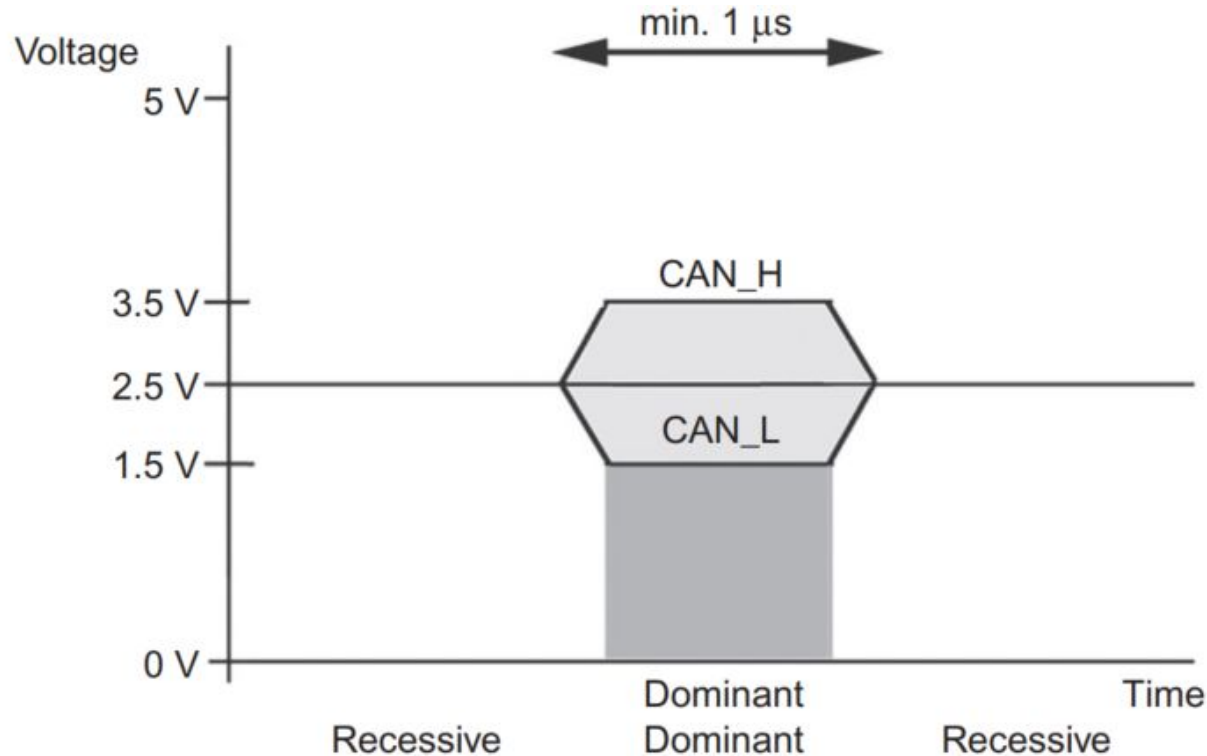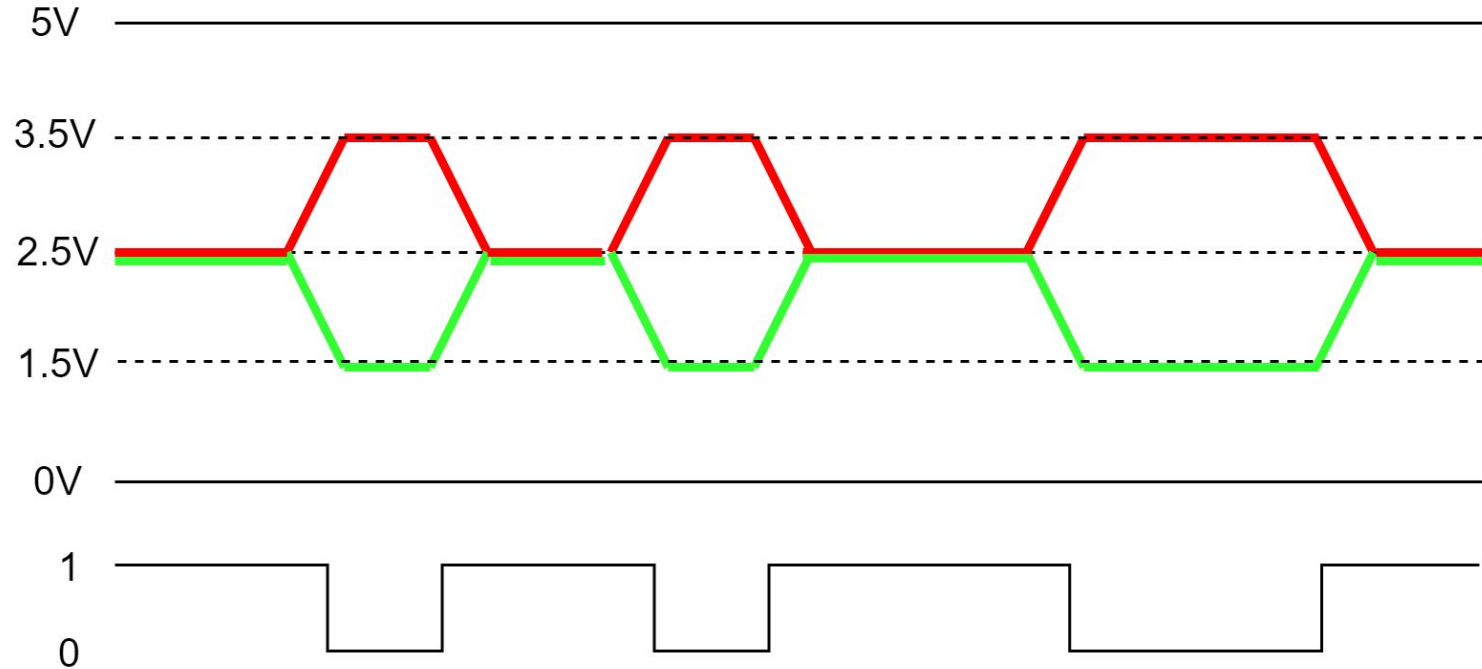
- The CAN bus is described by a <u>data link</u> and <u>physical layer</u>

- ISO 11898-1 describes the data link layer, while ISO 11898-2 describes the physical layer

- From ISO 11898-2:

  - CAN nodes must be connected via a two-wire bus with baud rates up to 1 Mbit/s or 5 Mbit/s (CAN FD)
  - Maximal cable lengths should be between 500 m (125 kbit/s) and 40 m (1 Mbit/s)
  - The CAN bus termination must be a 120 Ohms resistor

- The standard CAN frame is composed by 8 message fields

- CAN 2.0A and 2.0B differ in the length of the ID field



Message fields of the CAN frame

# CAN Frame Message Fields
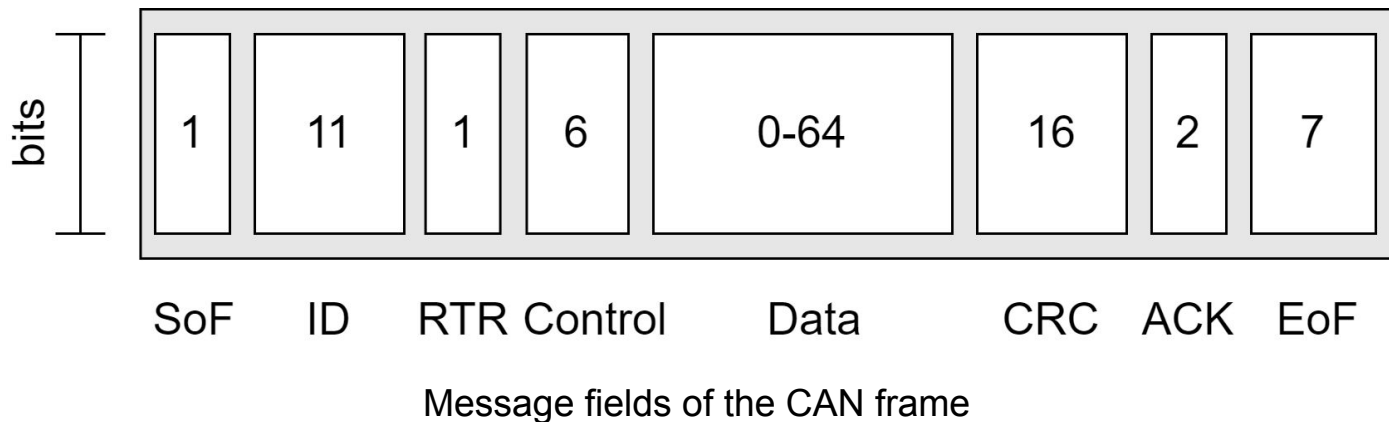
- **Start of Frame (SoF):** dominant 0 to tell the other a node wants to talk

- **ID:** frame identifier. The lower the ID, the higher the priority. It is <u>not</u> an identifier of the sender

- **Remote Transmission Request (RTR):** indicates whether a node sends data or requests data from another node

- **Control:** contains the Identifier Extension Bit (IEB) which is dominant 0 for 11 bits. It also contains the 4 bit Data Length Code (DLC) that specifies the length of the data bytes to be transmitted (0 to 8 bytes)

# CAN Frame Message Fields

- **Data:** payload in common network terminology. CAN signals that can be extracted and decoded for information

- **CRC:** check for data integrity

- **ACK:** indicates whether a node has acknowledged and received data correctly

- **End of Frame (EoF):** end of the CAN frame
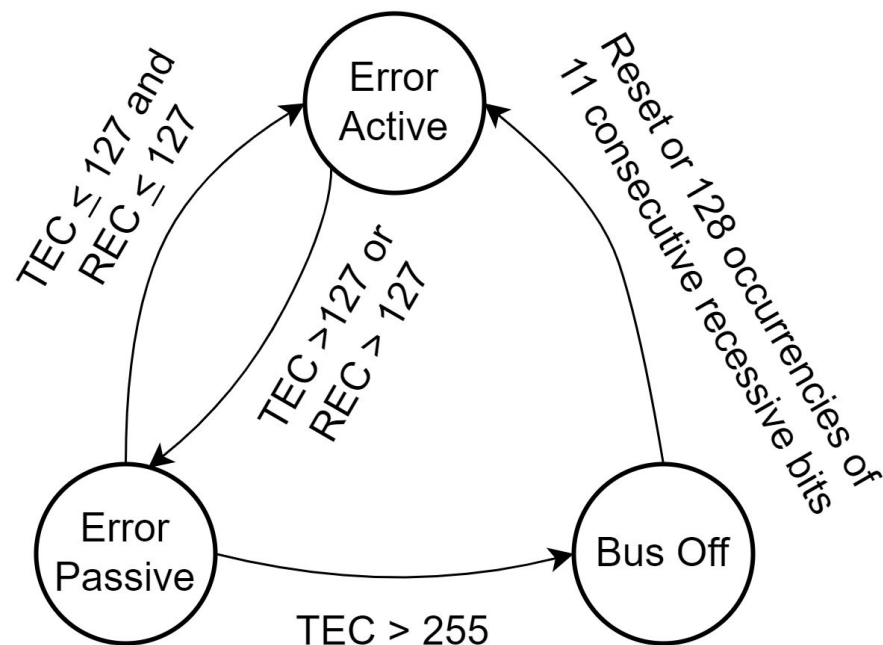
# Validity of the CAN Frame

- CAN frames need to satisfy certain conditions to be valid

- If a node detects its transmission of an erroneous message, it takes actions accordingly

- This is the CAN bus error handling, and each node has its own error counter and state

- The state is in the set (active, passive, bus off) depending on the counter value

# Validity of the CAN Frame

- Counters are Transmit Error Counter (TEC) and Receive Error Counter (REC)

- TEC = TEC+ 8 if an error occurs during transmission

- REC = REC + 1 if an error in the reception

- Success decreases the counter by one in both cases

- Nodes start at the error active frame

- A node transitions to the error passive state if the value of the counter exceeds 127

# Validity of the CAN Frame

- In the error passive state the node can only write recessive error flags, thus not affecting the bus traffic

- The node transitions to the Bus off state is the counter exceeds 255

- In this case, the node no longer takes part to the bus traffic

- To get back to error active, the node needs to be either reset or should count 128 occurrences of 11 consecutive recessive bits

# Validity of the CAN Frame

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Error detection and fault confinement states

# Bus Off Mode

- When an ECU transitions to the bus off mode it means that something serious is happening

- To prevent accidents but still allow the driver to reach a safe place, the ECU in bus off usually runs with predefined parameters and reduced functionality (e.g., limited RPM)

- We call an ECU in this state as *limp home*

- In this state, warning limps are turned on on the driver's dashboard

- Depending on the severity, the limp mode is eventually disabled

- In CAN bus transmissions we can have no less than five types of errors

1. *Bit error*: occurs when an ECU, after comparing its transmitted bits with those on the CAN bus detects a mismatch (does not hold in arbitration mode)

2. *Stuff error*: after transmitting five consecutive same polarity-bits, the ECU sends an opposite bit to maintain soft synchronization. An error occurs if stuffing does not happen

3. *CRC error*: computed one different from the received one

- In CAN bus transmissions we can have no less than five types of errors

4. *Form error*: if a fixed-form bit field (e.g. EoF) has a bit error the ECU raises a form error

5. *ACK error*: when a node receives a frame it responds with a dominant bit in the ACK frame. If none respond, then ACK error

# Error Flags

- When a node detects an error it needs to warn the others on the bus

- The node raises an *error flag* which may come in two forms: active and passive

- Nodes that are in **error-active mode** issue an *active error flag* which consists of 6 dominant bits

- The transmitted frame causes other nodes to violate the bit-stuffing rule, transmit their own error frame caused by the stuff error, and terminate any on-going transmissions or reception

# Something More on Errors
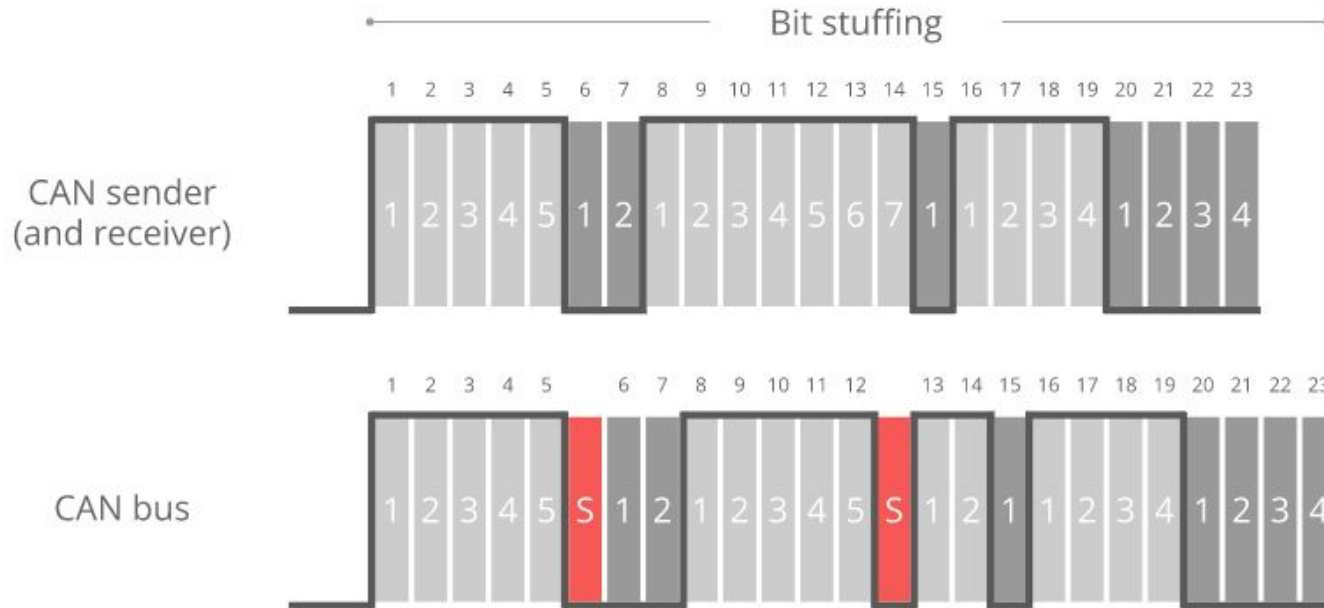


Every 5 consecutive bits of same polarity, add one for synch

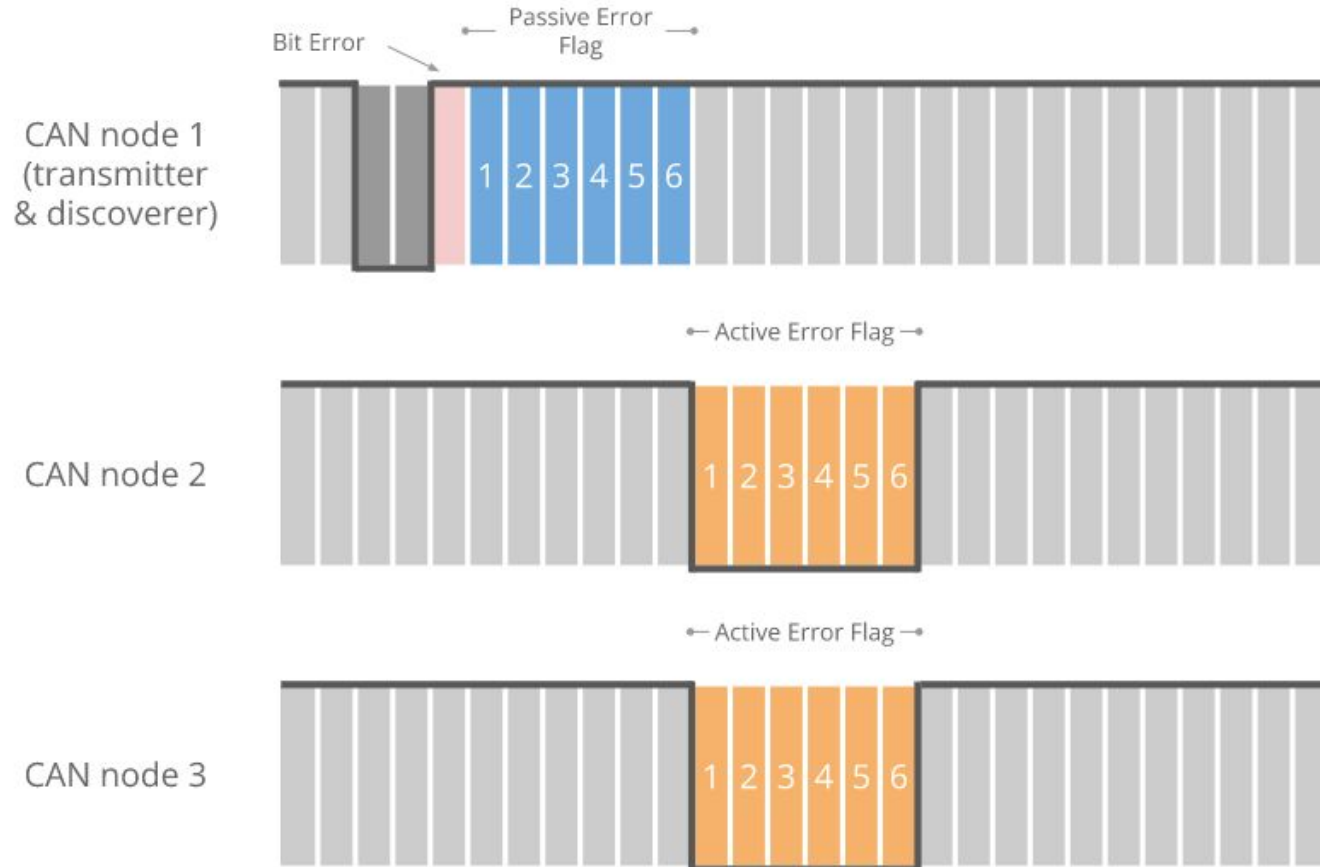See source on: https://www.csselectronics.com/pages/can-bus-errors-intro-tutorial

- Bit stuffing error is a violation of this rule and is visible to all CAN nodes

- Hence, we can have a bit error that makes the transmitter raise this flag, and all other nodes raise this error to notify the overall CAN

- We call them as *primary Active Error Flag* and  *secondary Active Error flags*

- When the node is in passive error mode, and is transmitting, it can only transmit recessive bits as error flag

- This is in turn detected as a bit stuffing error by all other nodes

- If all other nodes are in error active, they will create an active error flag

- If instead the error passive node raises an error passive flag while receiving, this will not be detectable by other nodes in th network

# Passive Error Flags

# Bus Arbitration

SPRITZ
SECURITY & PRIVACY
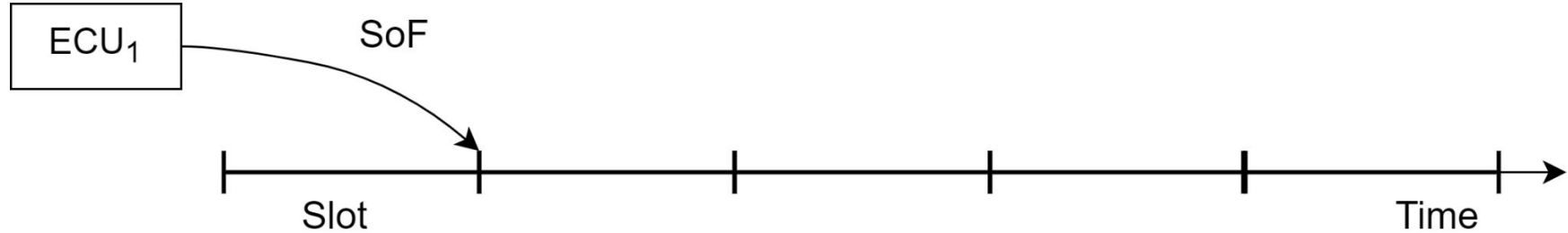RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

- It refers to the process by which nodes get a share of the bus resources to transmit

- CAN arbitration protocol is both priority-based and non-preemptive

- Non-preemptive: a message cannot be preempted by a higher priority one if this was queued after the transmission began

- The media access protocol alternates contention and transmission phases

# Bus Arbitration

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA
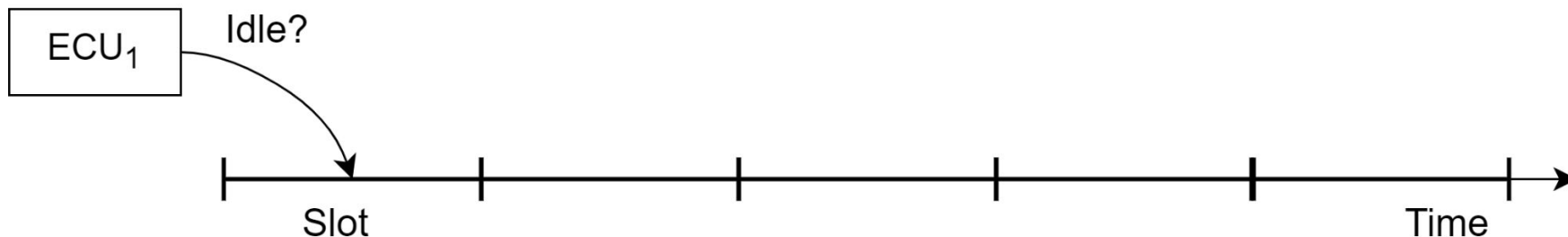
- Time is divided into slots, each with a length sufficient for a message to go back and forth in the whole bus
- A node wishing to transmit checks whether the channel is idle

- If idle, it waits the next slot and start a contention phase by transmitting a SoF bit

# Bus Arbitration

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA
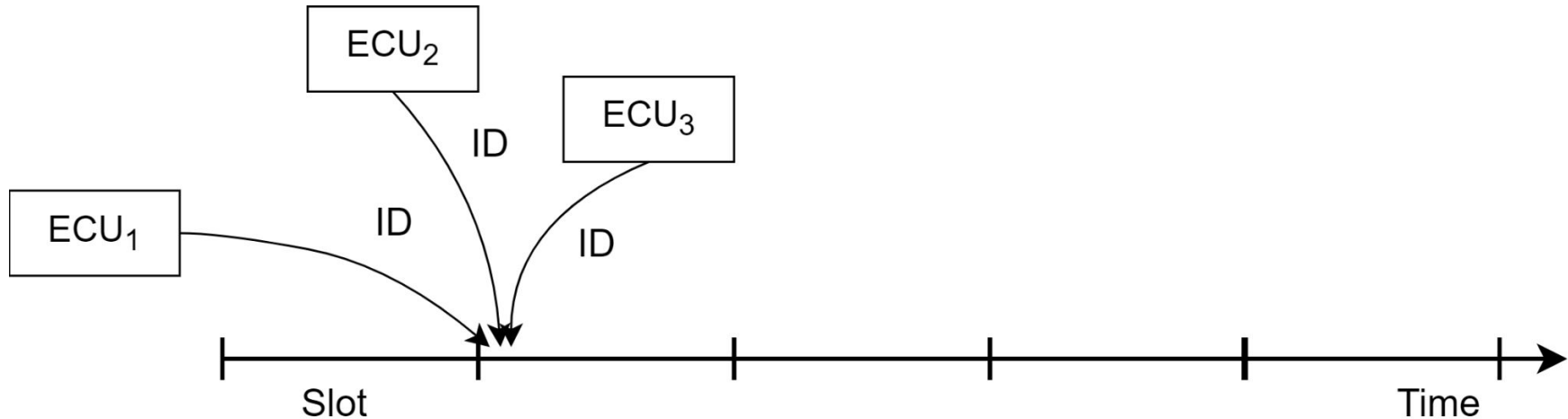


- All other nodes wishing to transmit send their ID

- The CAN controller compares its output with the actual bus level at the end of each bit cycle

# Bus Arbitration

SPRITZ
SECURITY & PRIVACY
RESEARCH GROUP

UNIVERSITÀ
DEGLI STUDI
DI PADOVA
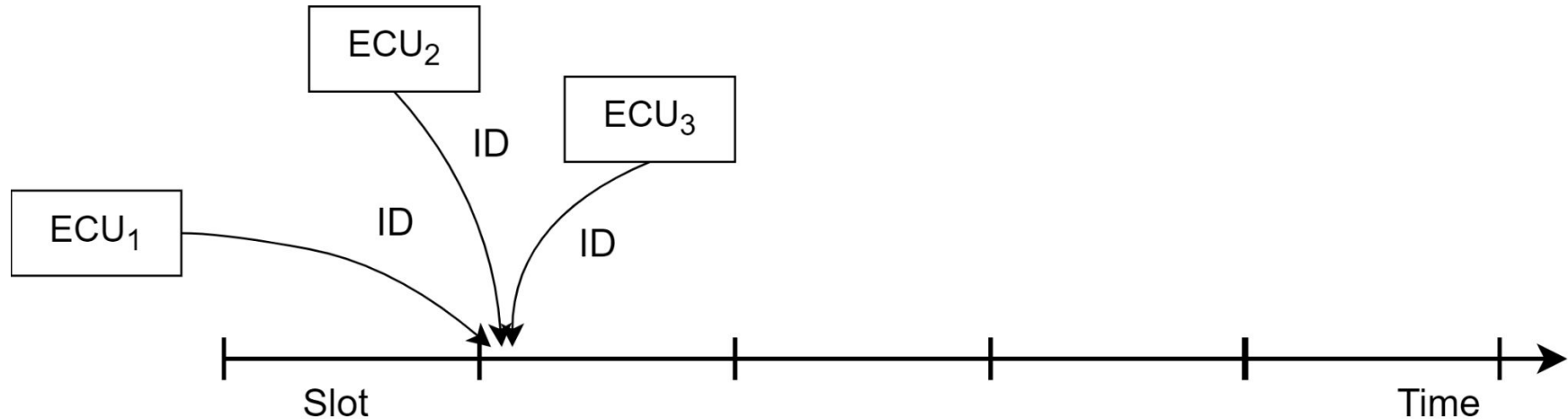
- The node loses contention in case it submitted a recessive level (high) and detects a dominant level (low)

- Error is dominant transmitted and recessive detected

| S1  | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
|-----|---|---|---|---|---|---|---|---|
| S2  | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 |
| S3  | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| Bus | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 |

S3 wins the arbitration at the 7th bit

- After the node that wins the competition terminates its transmission with an EoF, there should be new transmissions

- The CAN bus uses a 3 bit inter-frame symbols to separate packets

- After this, the bus becomes idle again and arbitration shall commence again

# Accessing CAN Bus





- To access CAN bus you need to connect to the On Board Diagnostic (OBD) port
- Basically all cars nowadays use the OBD-II standard port
- It is usually located near the driver's or passenger's seat
- To talk with the CAN bus you need a converter, such as that in the figure
- This converts CAN bus data to something readable via a USB port

- The bus-off attacks is a denial of service attack that exploits how ECUs access the bus

- Proposed by Cho et al. in 2016 (pretty recent, nah?)

- The goal of the attacker is to compromise the network and in particular multiple healthy (i.e., non compromised ECUs) with a minimal number of messages

- Notice that this is very different from flooding

- The attacker can compromise an in-vehicle ECU either physically or remotely to gain its control

- We do not require the adversary to reverse engineer messages or checksums to be able to deliver the attack

- Once the ECU is compromised, the attacker can inject messages with any ID, DLC and data on the CAN bus

- The error handling mechanism of CAN bus forces ECUs that measure a certain number of errors to go bus-off

- The attacker exploits this feature of CAN bus to iteratively isolate ECUs

- Injecting attack messages, the adversary coerces the TEC of an uncompromised/healthy victim ECU to continuously increase

- Eventually, the attacker forces the error confinement to force the victim or even the entire network to shutdown

- Suppose that a victim V periodically sends a message M

- The attacker can hence deliver a successful bus-off attack by (all

  conditions must be fulfilled)

  - Using the same ID
  - Transmitting at the same time as M
  - Having at least a bit that is dominant in the attack message while being
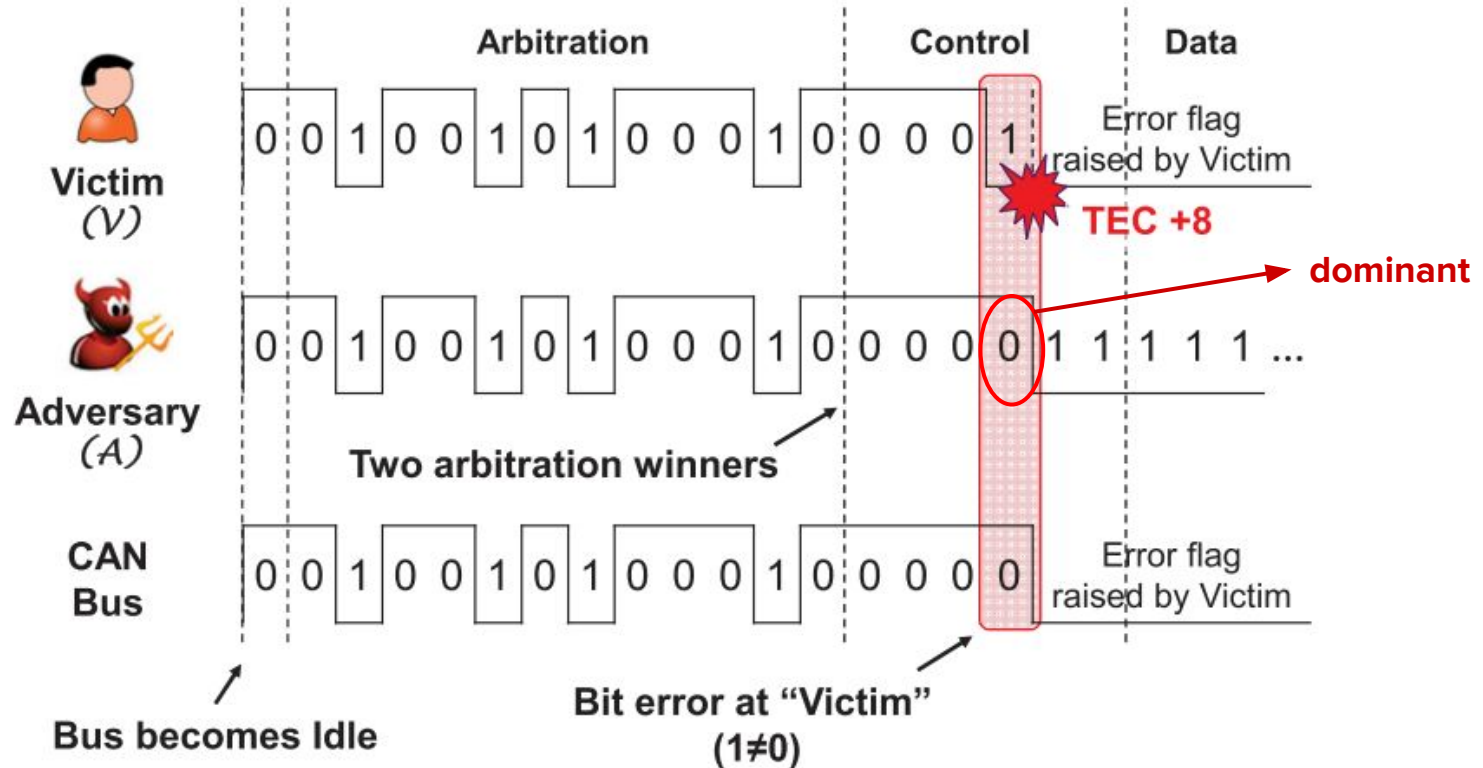    recessive in M (all preceding bits are equal)

Figure from the original paper: "Error handling of in-vehicle networks makes them vulnerable"

- **Phase 1: Victim in Error-Active**

- Both adversary and victim start in error-active mode, and the attacker targets one of the victim's periodical messages

- The attacker sends the malicious message and the victim's TEC increases

- The attacker's TEC also increases, due to the stuff or bit errors triggered at the adversary node

- Both nodes automatically retransmit the failed message

- **Phase 1: Victim in Error-Active**

- Both adversary and victim start in error-active mode, and the attacker targets one of the victim's periodical messages

- The attacker sends the malicious message and the victim's TEC increases

- The attacker's TEC also increases, due to the stuff or bit errors triggered at the adversary node

- Both nodes automatically retransmit the failed message
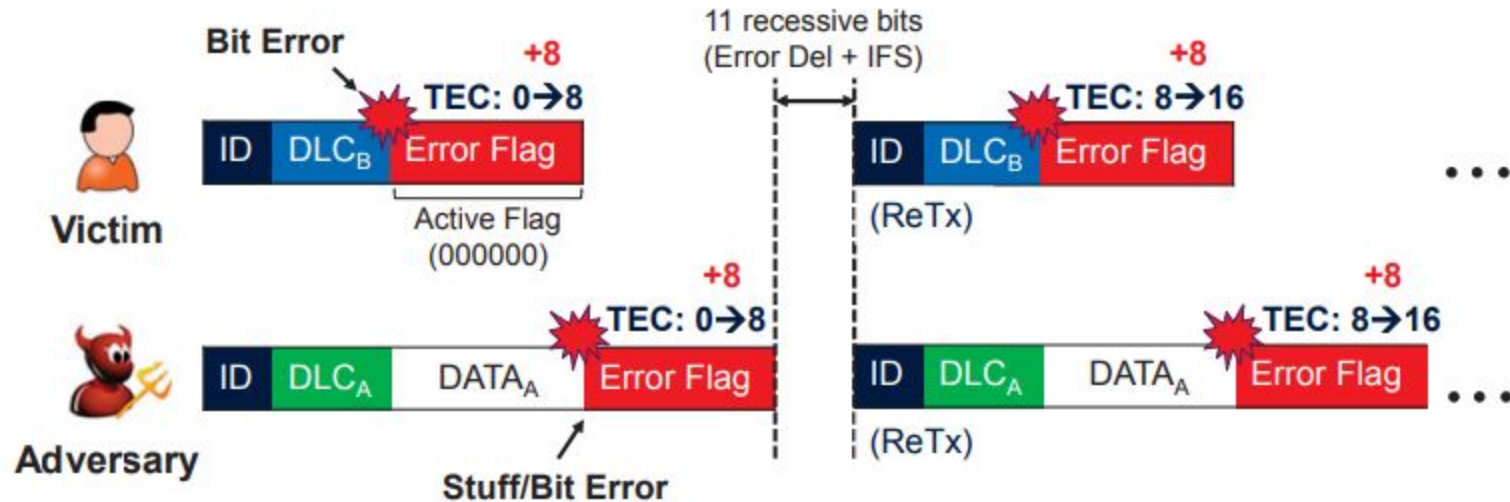
(a) Phase 1 – Victim in error-active mode.

- Thanks to the automatic retransmission, the attacker bring the victim to error-passive by sending a single message

- **Phase 1 to 2**

- After 16 retransmissions, both victim's and attacker's TEC=128 ➡ error-passive

- As a consequence, the victim attempts the delivery of a passive error flag with 6 recessive bits

- The attempt to transmit this flag persists until the end of the attacker's frame, after which it is successful (TEC = TEC -1)

- Due to the successful transmission, the adversary does not go to error-passive
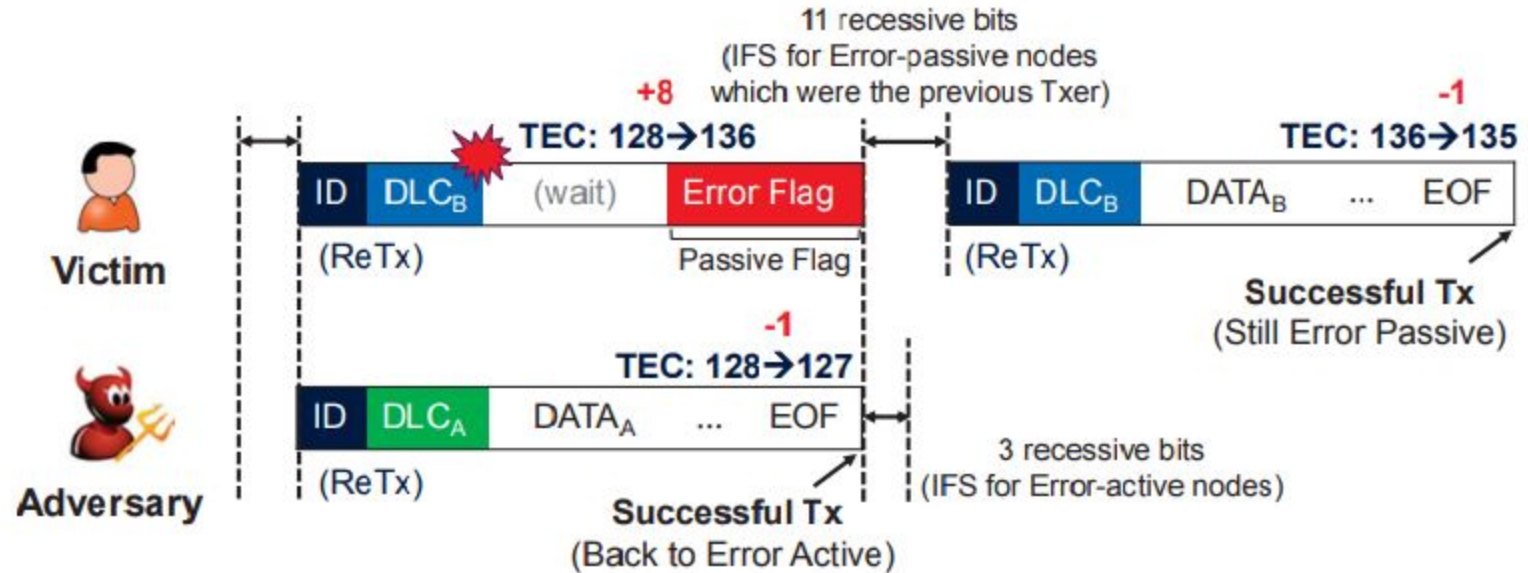
(b) Transition from Phase 1 to 2.
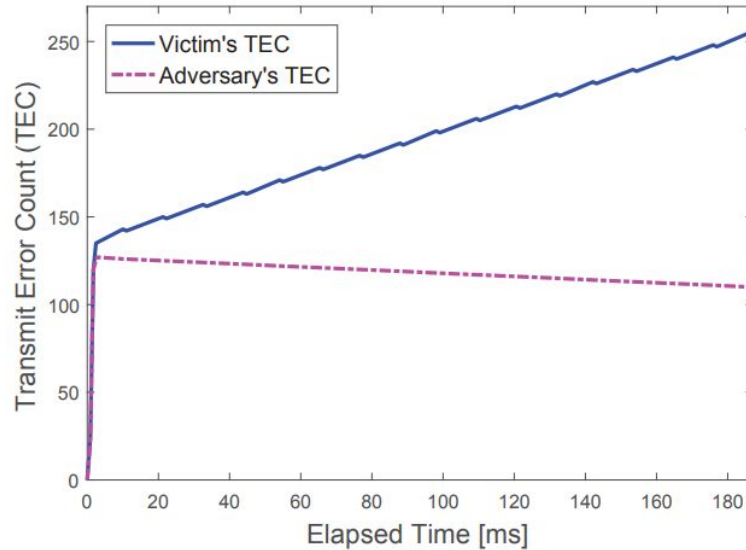
- TEC of victim and attacker differ

- **Phase 2: Victim Error-Passive**

- Once the scheduled interval of the target message is elapsed, V retransmits M again

- At the same time, the adversary reinjects malicious M

- Since the victim is in error-passive, the attacker's TEC decreases by 1, whereas the victim's increases by 7 (+8 -1) thus maintaining the error-passive

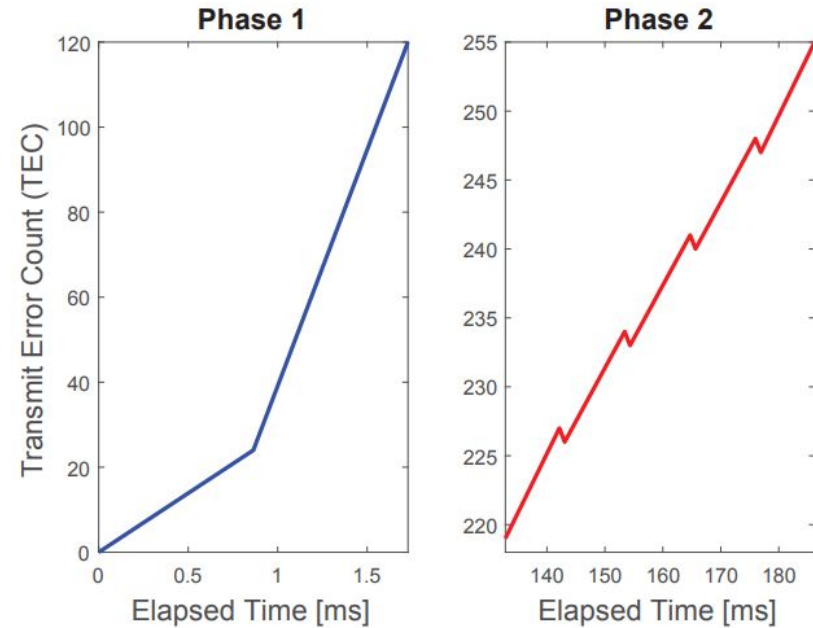- The attacker iterates until the victim's TEC>255, i.e., bus-off
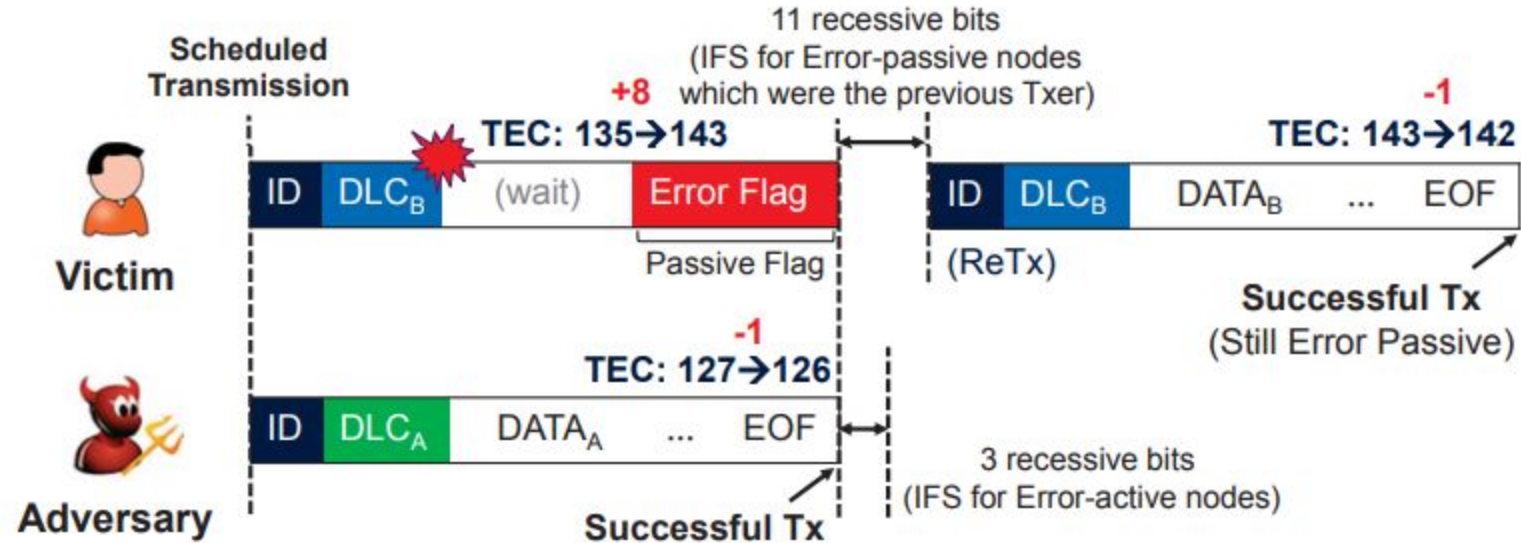
(c) Phase 2 – Victim in error-passive mode.

- TEC of victim and attacker differ

- TEC of victim and attacker
- TEC of victim

# Important Note

- Remember that CAN ID do not contain actual information on the transmitter

- The ID contains information that define the time interval and priority (i.e., safety-critical) of messages

- The attacker should hence target low-value IDs (dominant) to disconnect possibly safety-critical ECUs

- Examples: acceleration, braking

# Difficulties in Setting the ID

- Each ECU cannot acquire the IDs of all received messages

- Only of those that pass through its message filter

- We can distinguish hence between *received* message and *accepted* message

- The attacker can only read the ID from accepted messages, thus meeting the requirements on the same ID depends on the filter of the victim ECU

- If there is no filter then done, but filters can be remotely manipulated

- The constraint on synchronization must be precis at a bit level

- Although CAN messages are periodic, jitter may impair the effectiveness of the attack

- However, all messages and priorities are periodic and we can exploit this to infer when a certain message is going to be transmitted

- The exact time is hence 3 bit-time after the completion of the preceded ID