In-Vehicle Security

CPS and IoT Security

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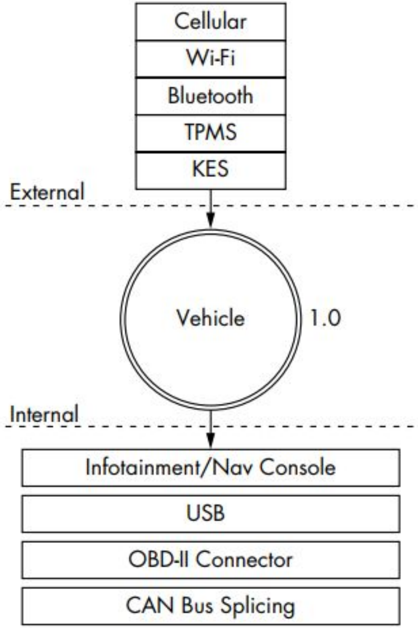
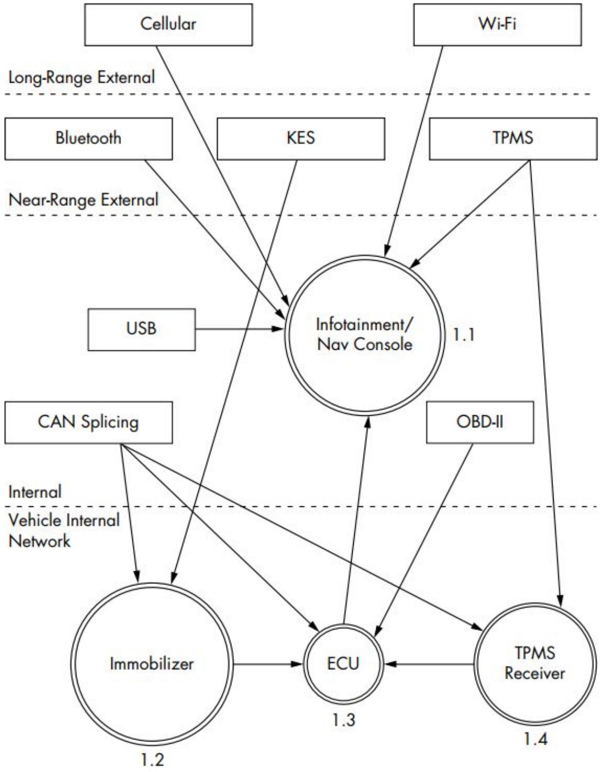
What is there in a Car?





Vehicle Components and Network

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- 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

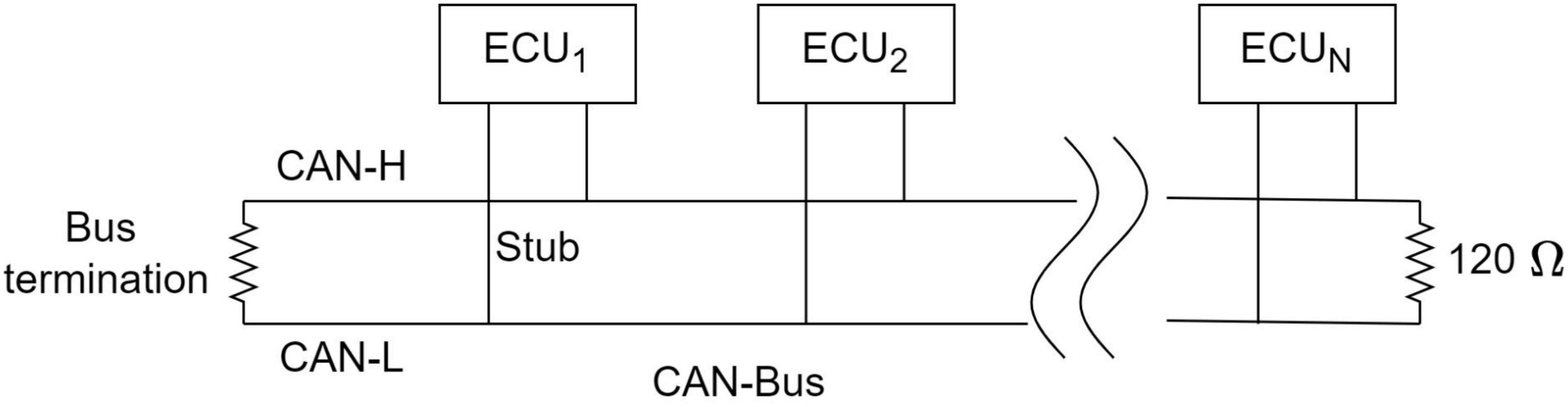
Why CAN Bus

- **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

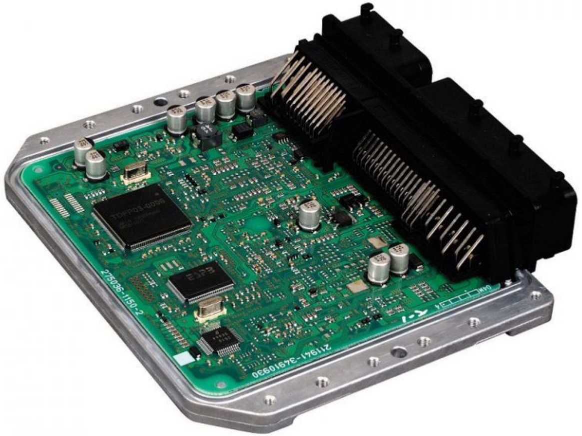
CAN Bus Wiring

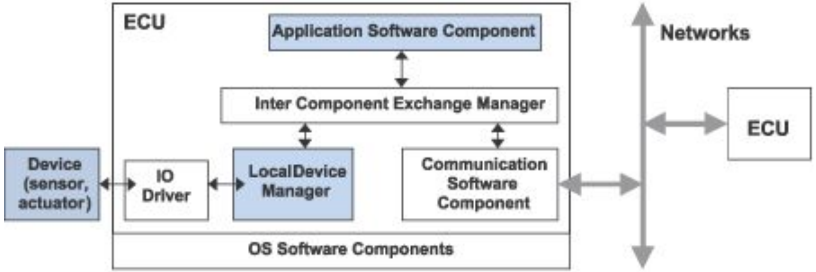
- To achieve reliability, it is important to prevent message collision such that no data gets lost
- Thanks to the shared bus and the message handling system, CAN allows for a reduced number of wires to achieve reliability
- Redundancy is the best way to achieve reliability, however it comes with a higher communication implementation cost (huge number of wires)
- Point-to-point communications were used before CAN

CAN Bus Architecture



Electronic Control Unit

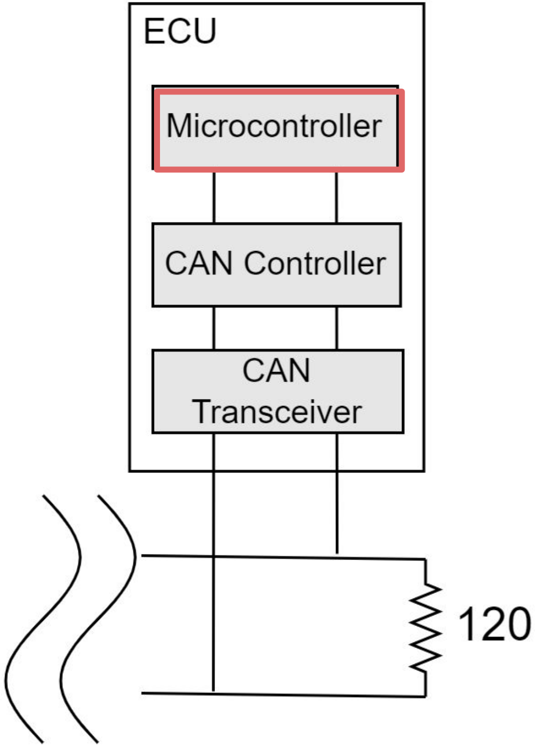




ECU Architecture

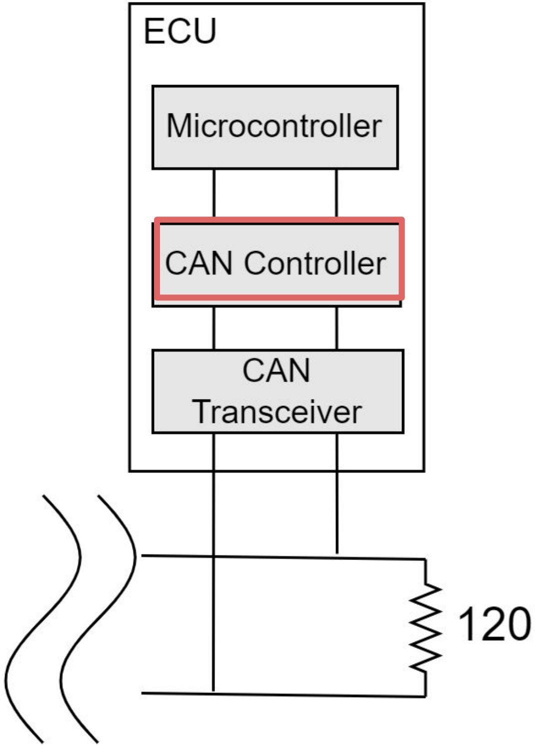
Microcontroller:

- 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 sensors and actuators



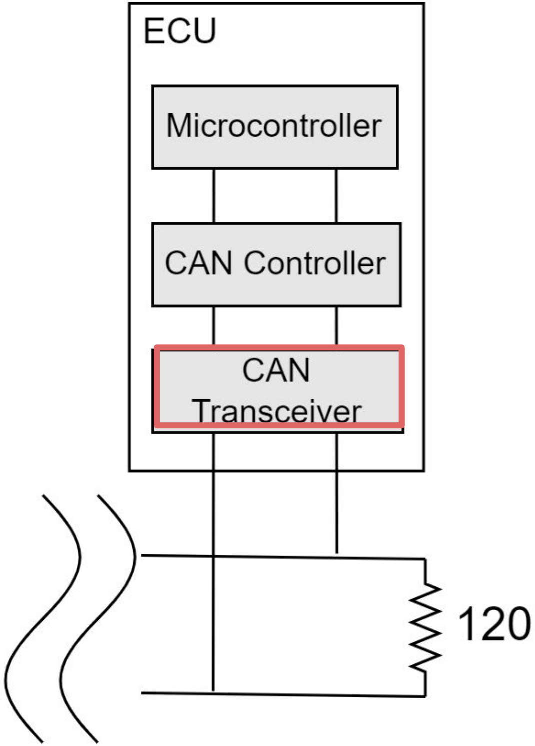
CAN controller:

- 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

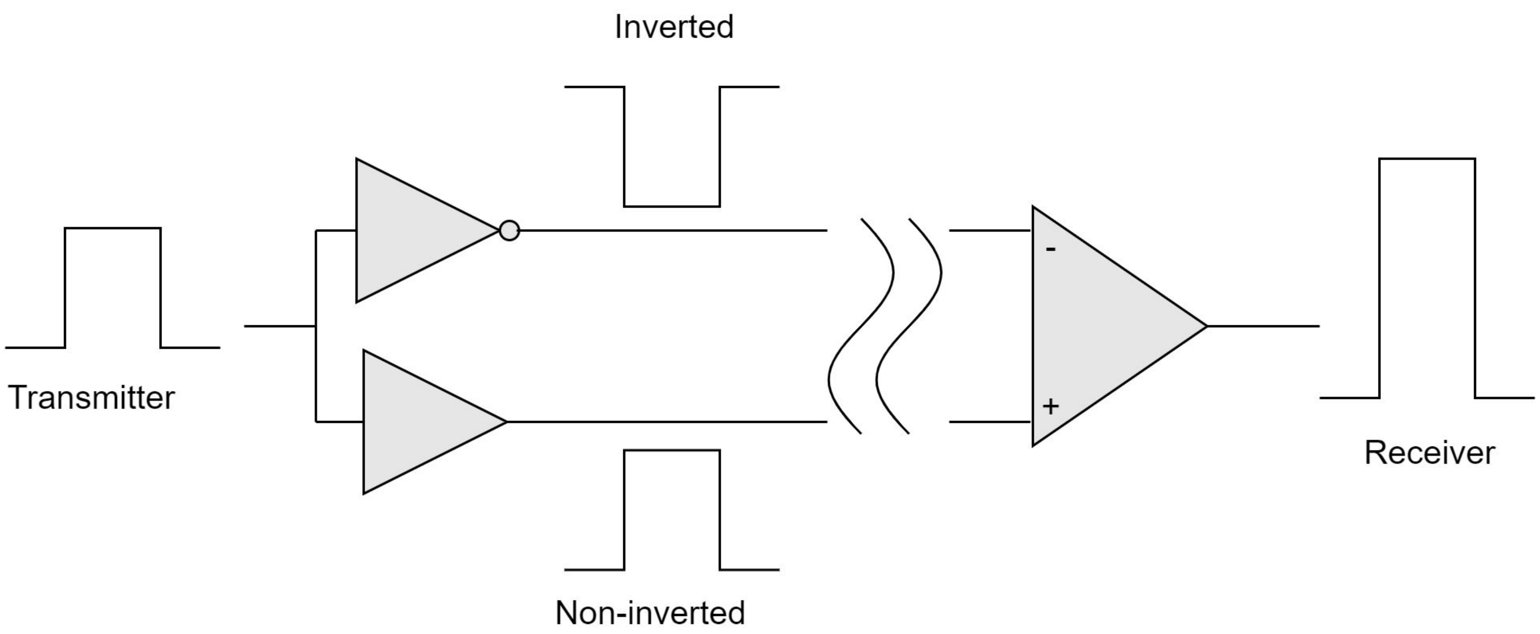


CAN Bus Communication

- 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

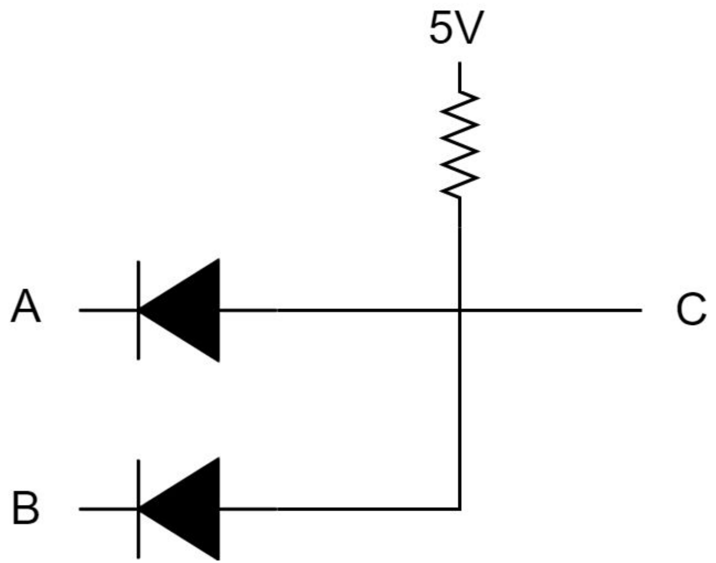
- CAN bus uses **differential** wired-AND signals



CAN Bus Communication

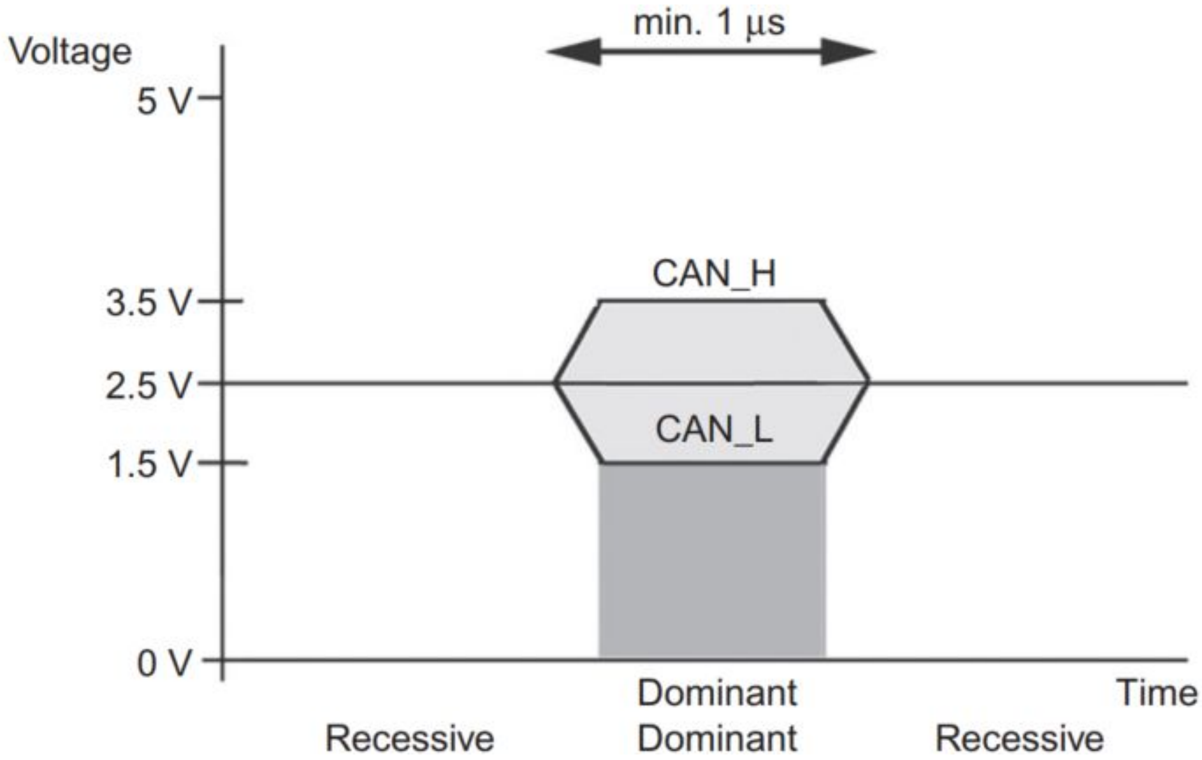
- CAN bus uses differential **wired-AND signals**

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



CAN Bus Communication

- Either dominant or recessive



CAN Bus Communication

- Dominant state = 0 bit
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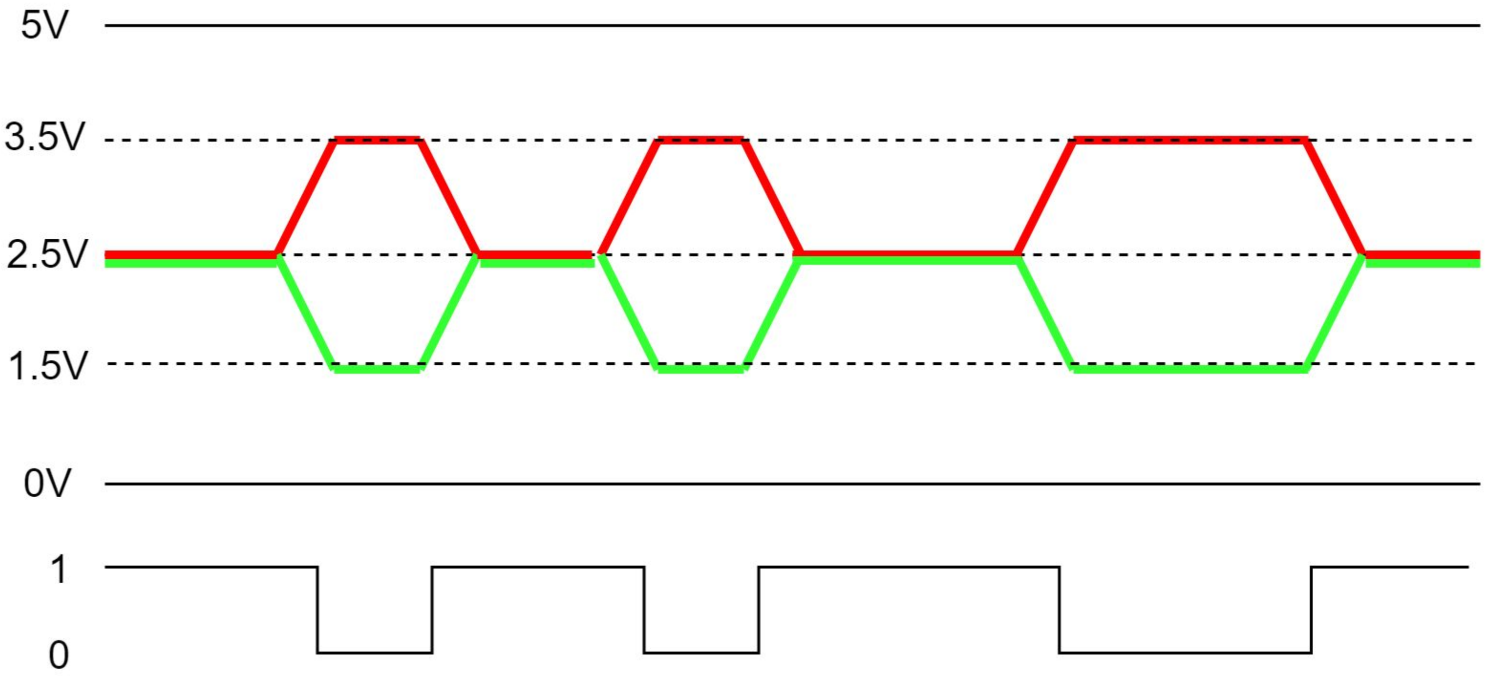
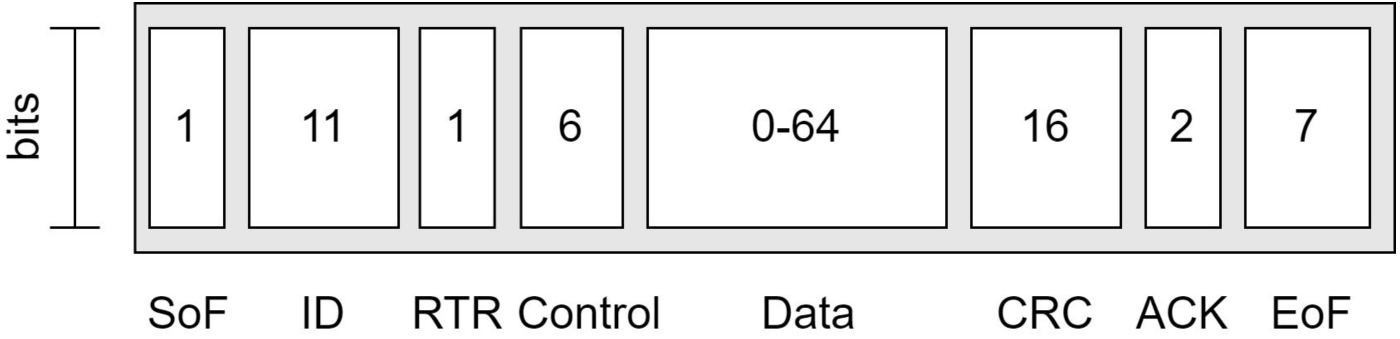


Physical and Data Link Layer

- The CAN bus is described by a data link and physical layer
- 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

CAN Frames

- 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 not 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

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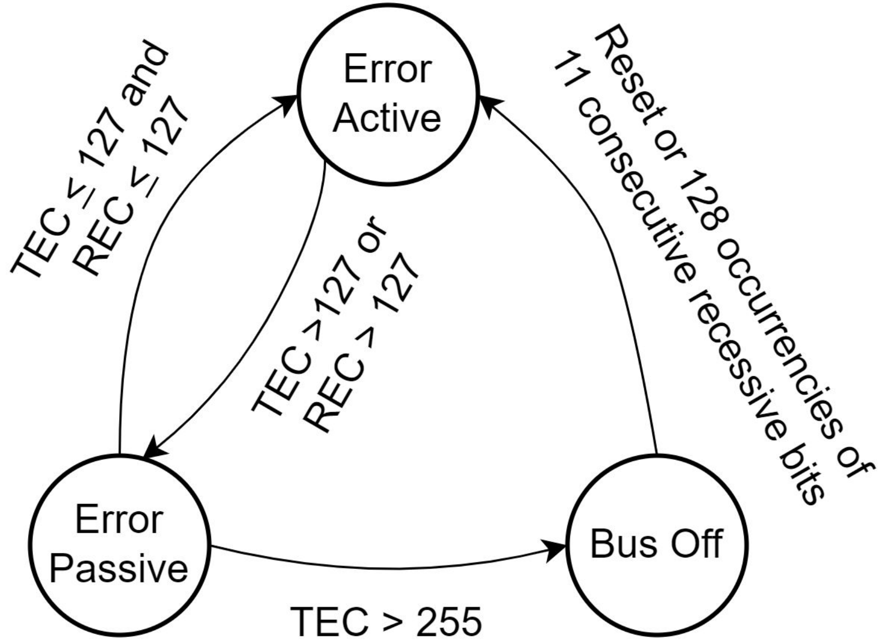

Error detection and fault confinement states

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

Errors in CAN Bus Frames

- 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

Errors in CAN Bus Frames

- 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

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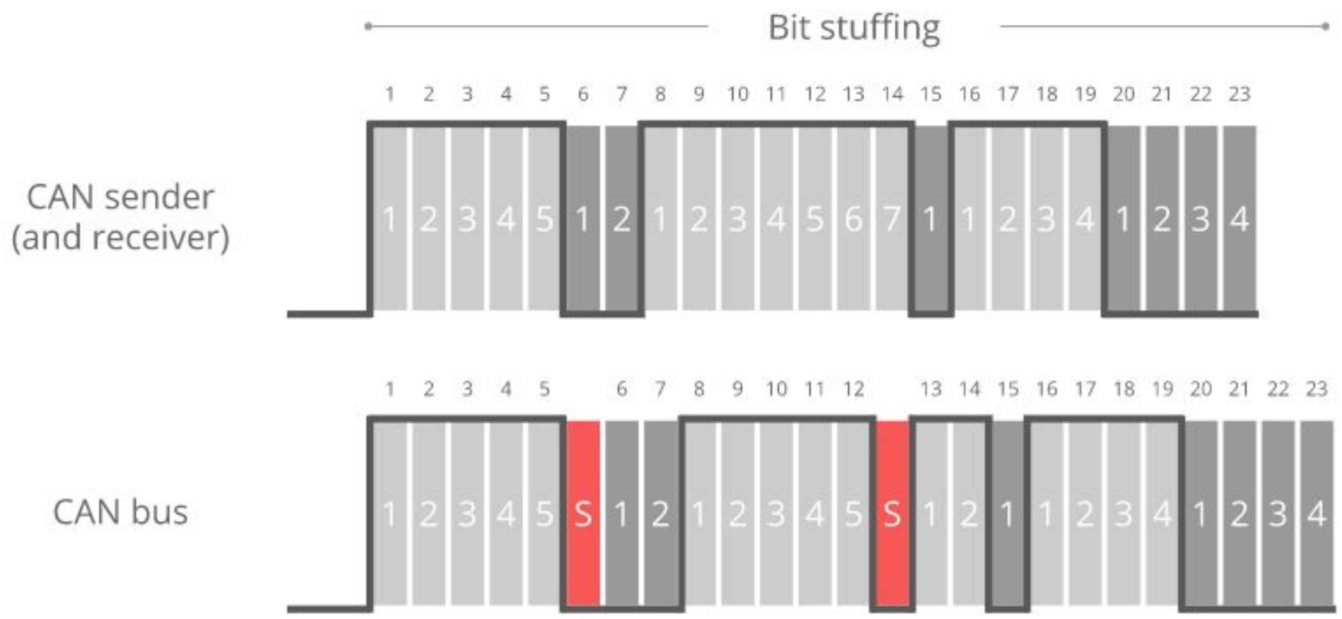


Every 5 consecutive bits of same polarity, add one for synch

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

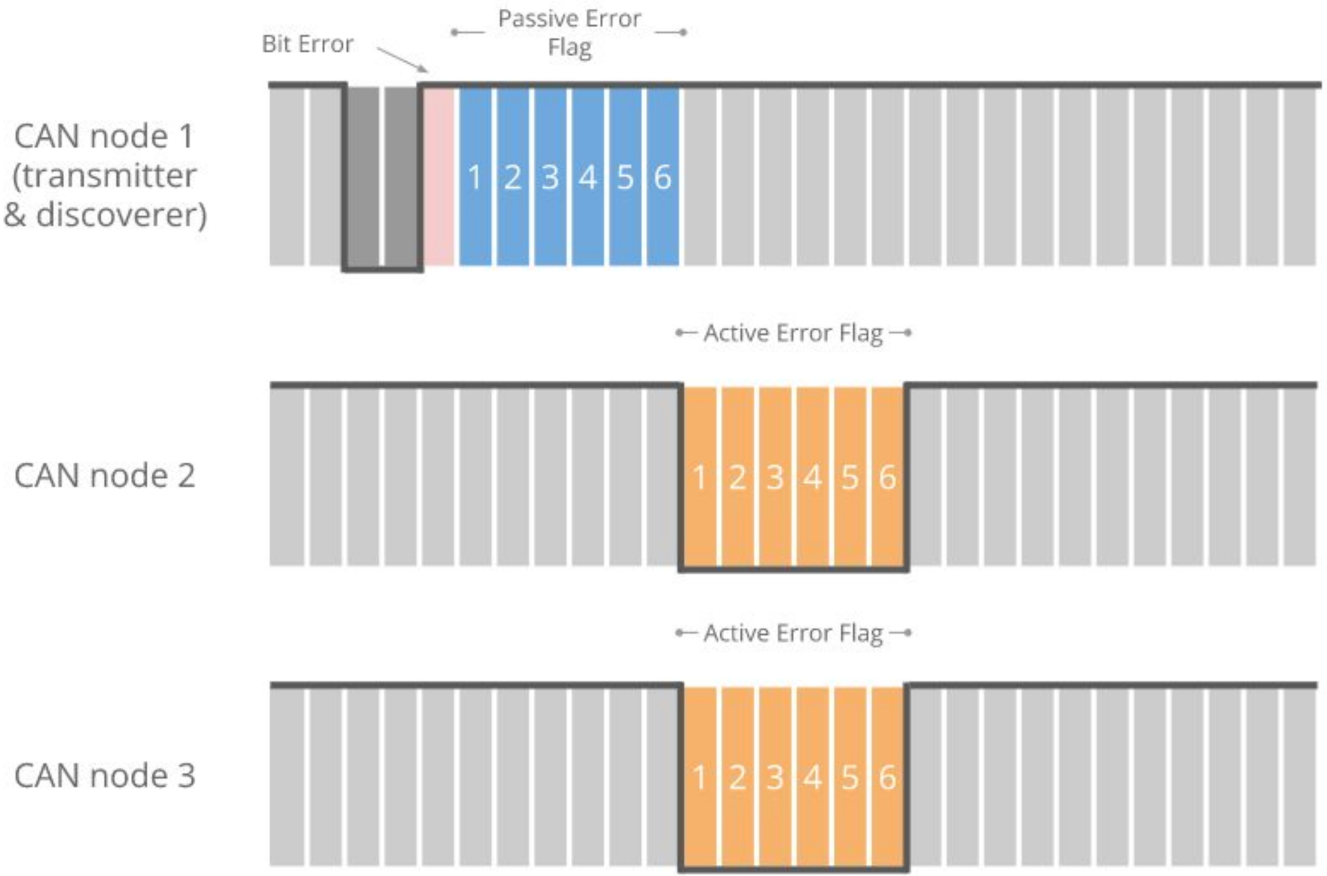
Error Flags

- 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*

Passive 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

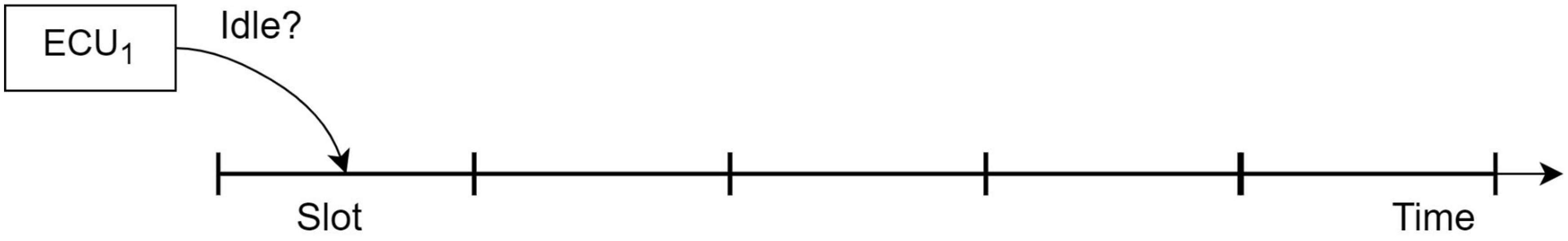
Passive Error Flags



Bus Arbitration

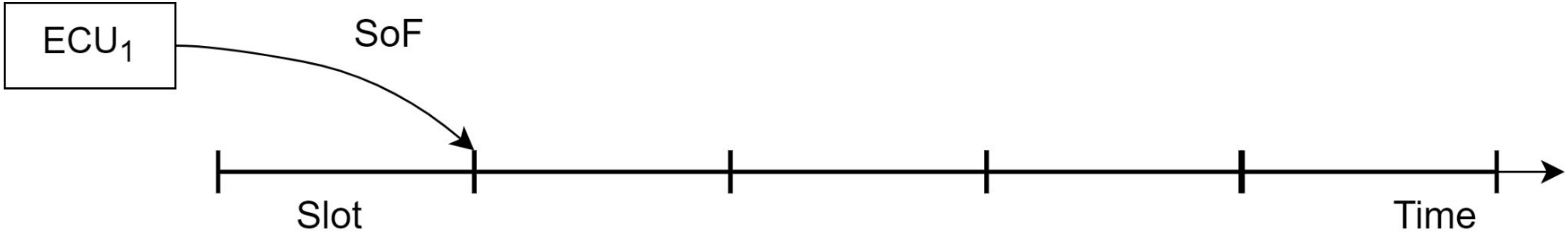
- It refers to the process by which nodes get a share of the bus resources to transmit
- CAN arbitration protocol is both priority-based and non-preemptive
- Non-preemptive: a message cannot be preempted by a higher priority one if this was queued after the transmission began
- The media access protocol alternates contention and transmission phases

Bus Arbitration



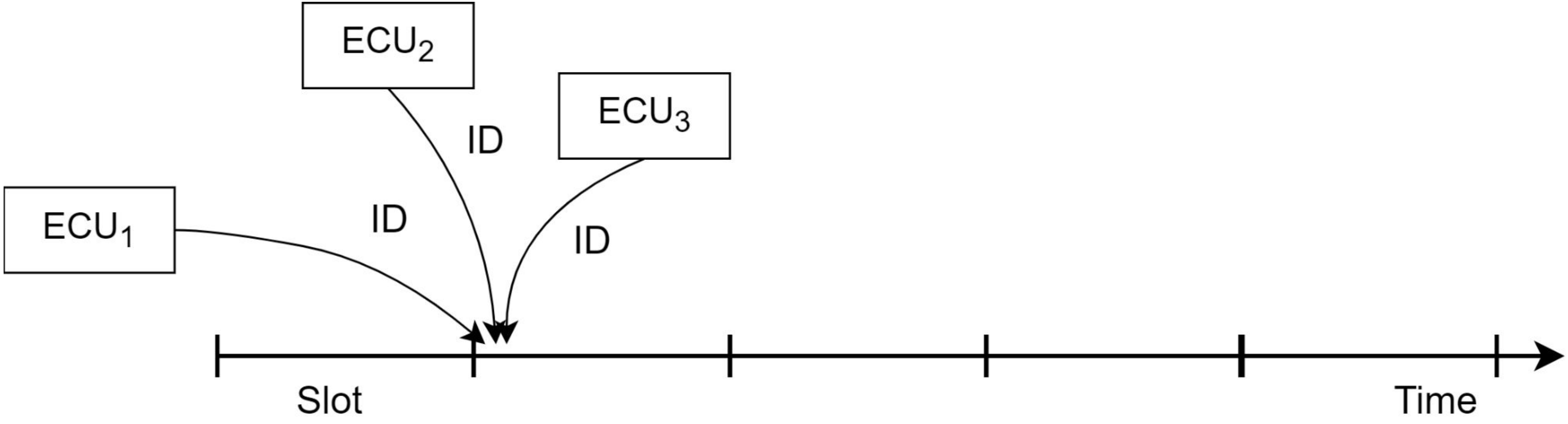
- Time is divided into slots, each with a length sufficient for a message to go back and forth in the whole bus
- A node wishing to transmit checks whether the channel is idle

Bus Arbitration



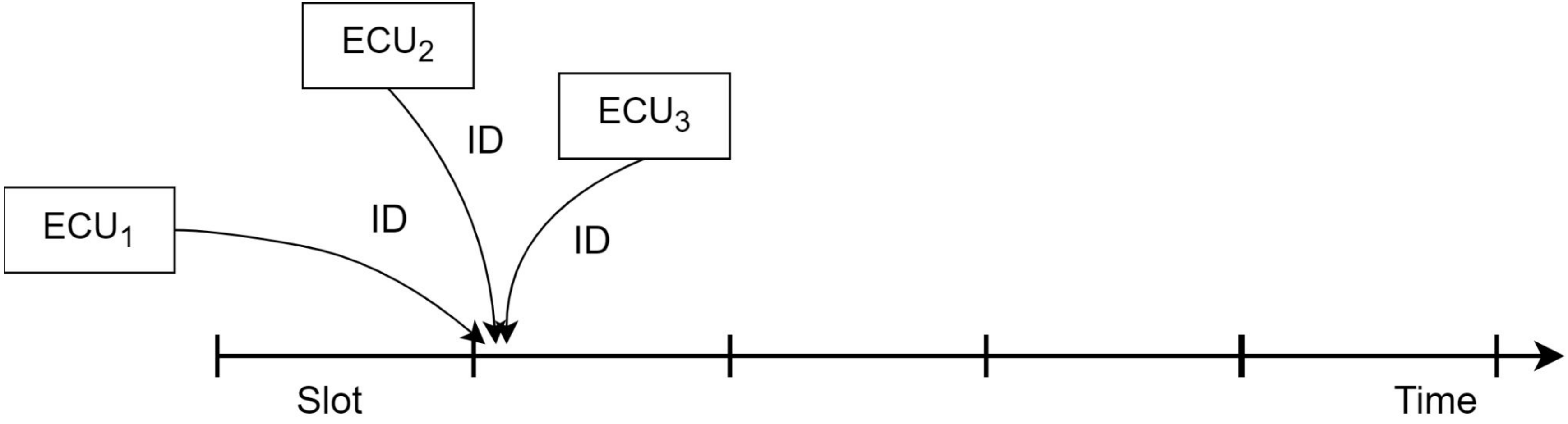
- If idle, it waits the next slot and start a contention phase by transmitting a SoF bit

Bus Arbitration



- 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



- 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

Bus Arbitration Example

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

Bus Arbitration

- 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

Sniffing CAN Bus Data

Practical Demo

The Bus-Off Attack

- 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

Bus-Off Attack: Adversary Model

- 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 Attack: Hint

- 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

The Attack

- 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)

The Attack

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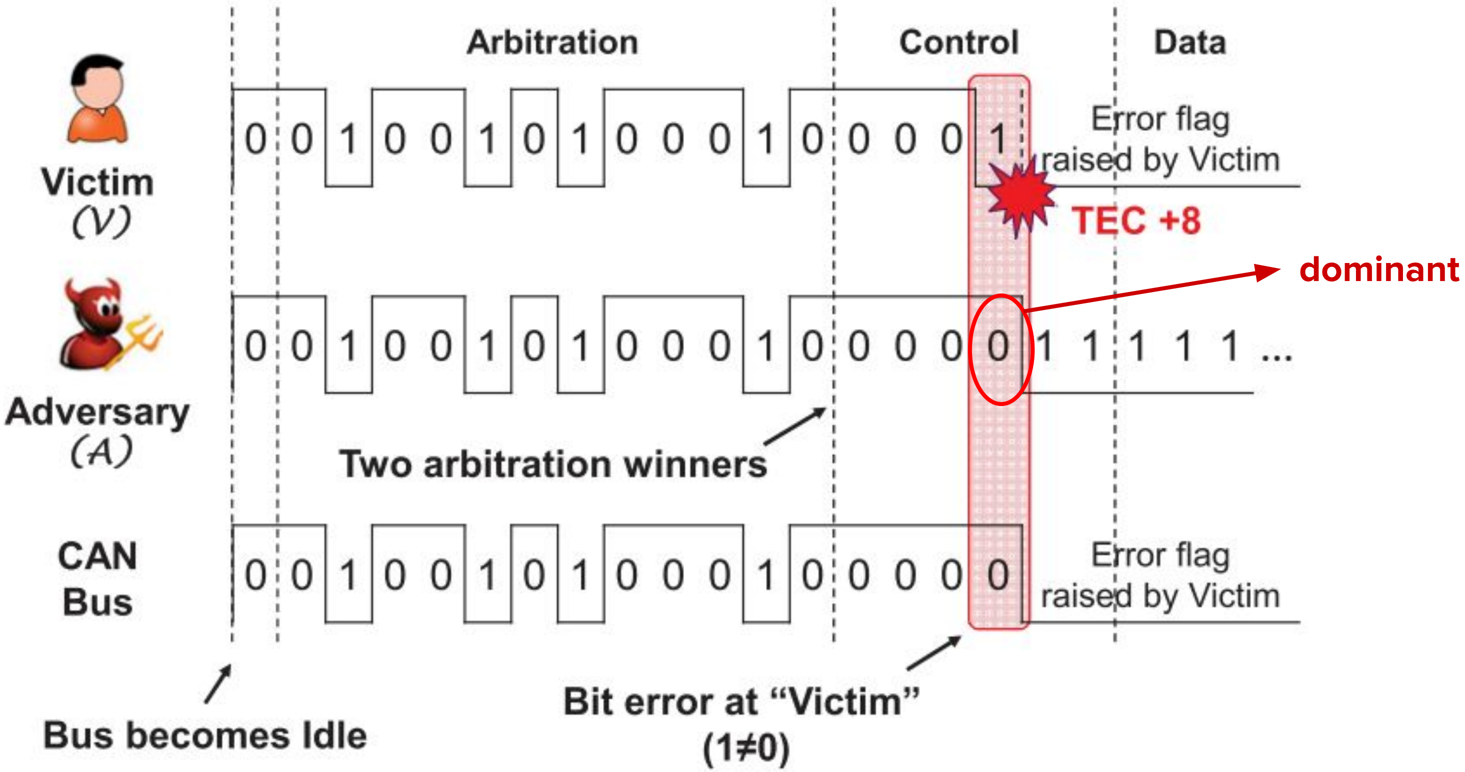

Figure from the original paper: "Error handling of in-vehicle networks makes them vulnerable"

Attack Phases

- **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

Attack Phases

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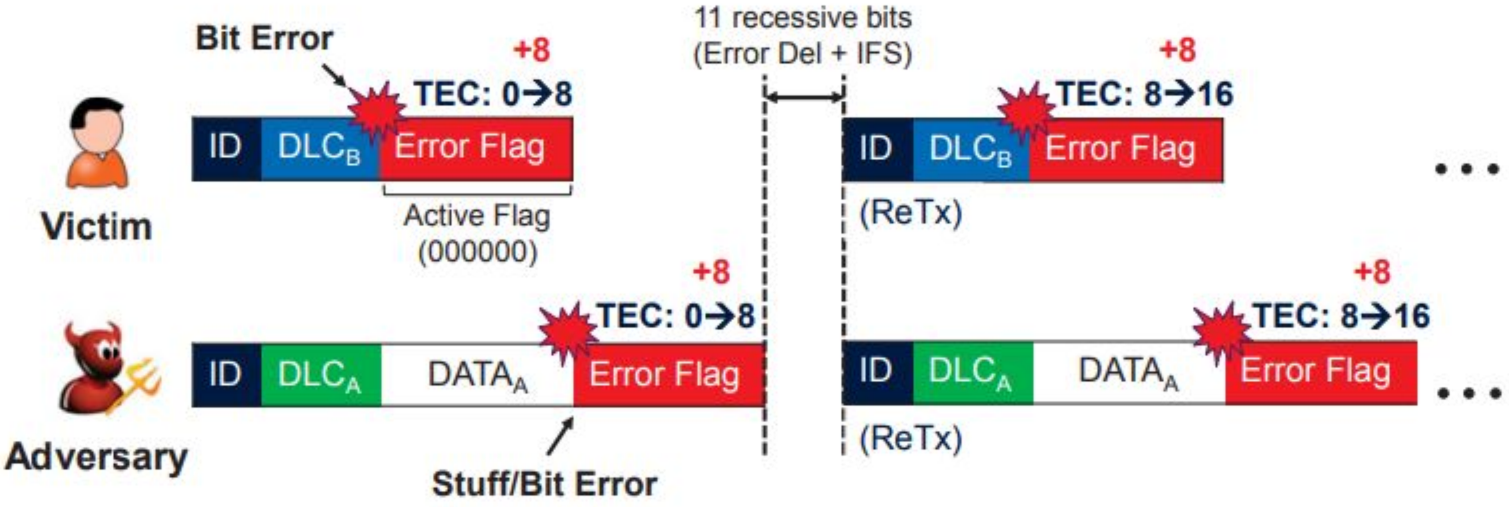
Phase 1



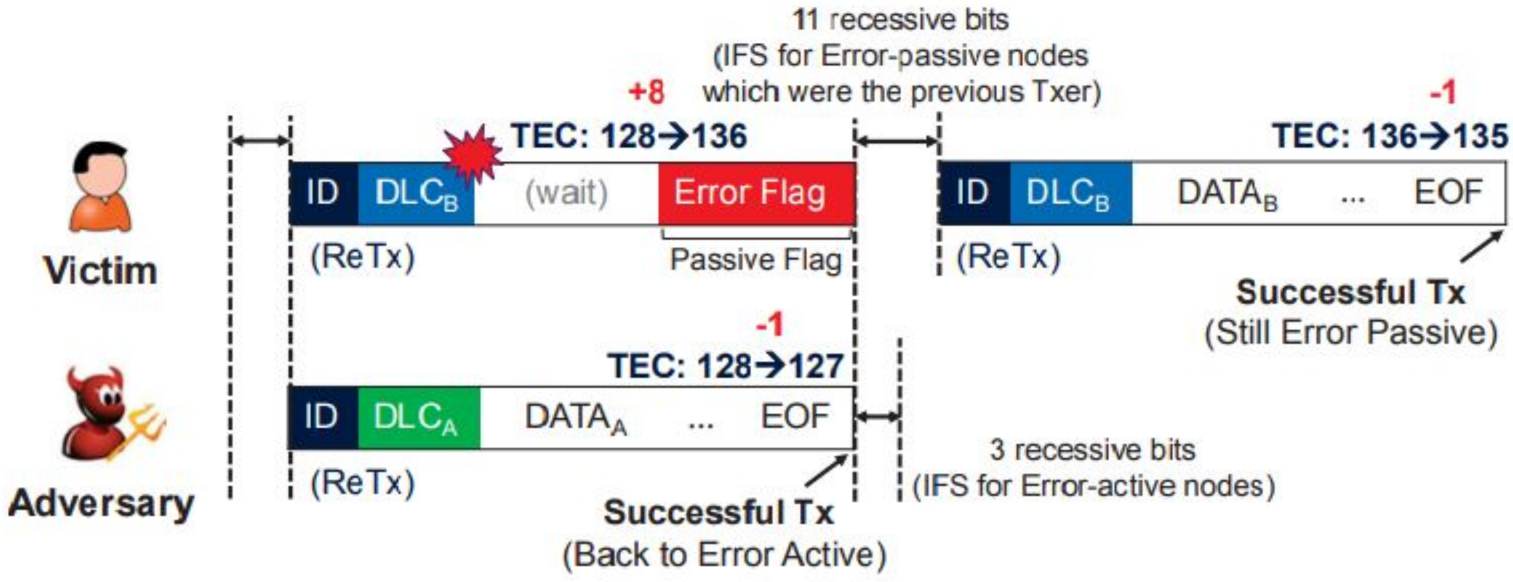
(a) Phase 1 – Victim in error-active mode.

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

Attack Phases

- **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

Phase 1 to 2



(b) Transition from Phase 1 to 2.

- TEC of victim and attacker differ

Attack Phases

- **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

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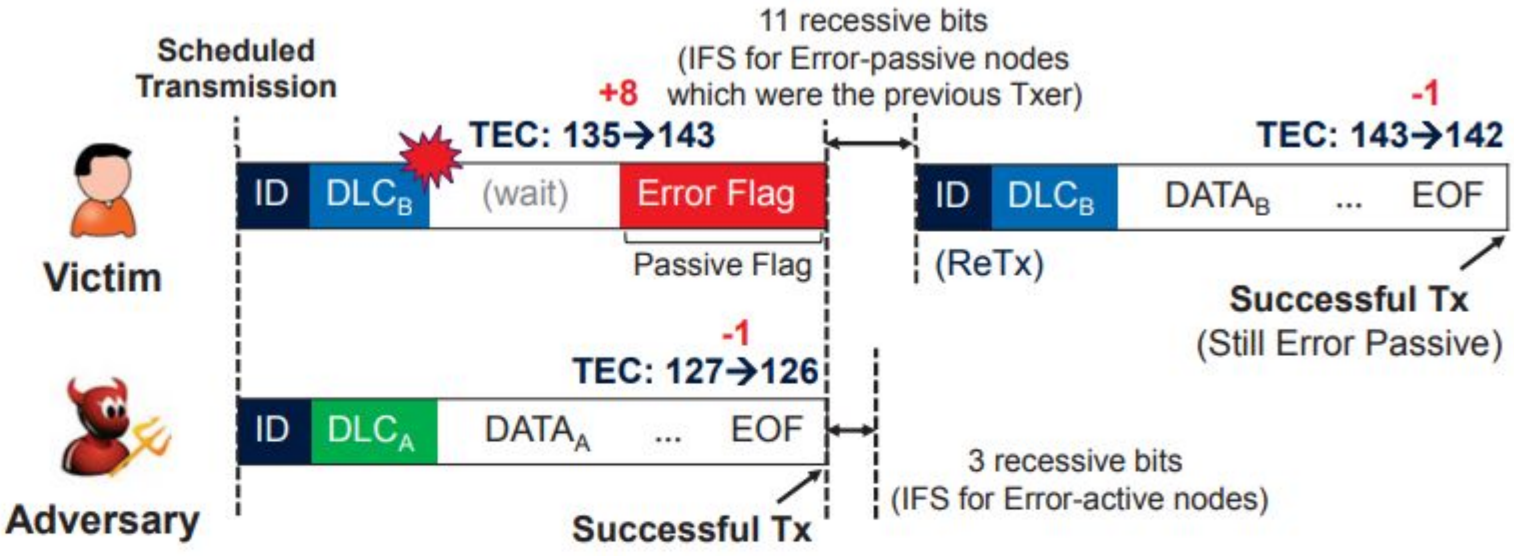
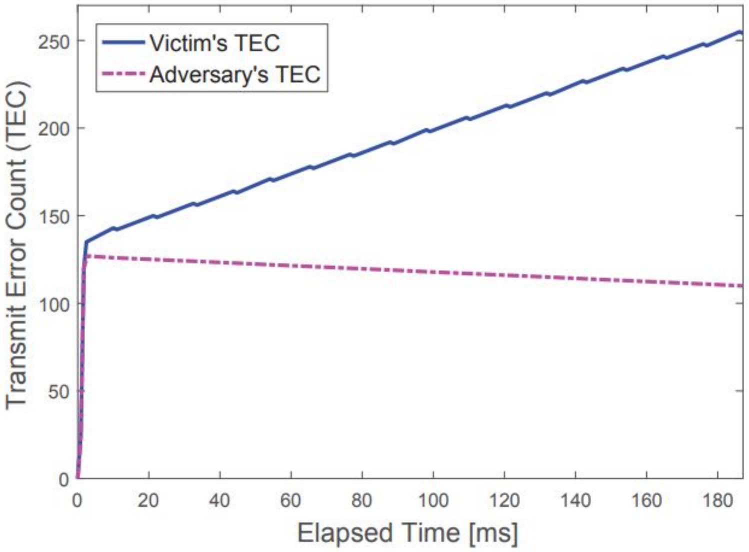
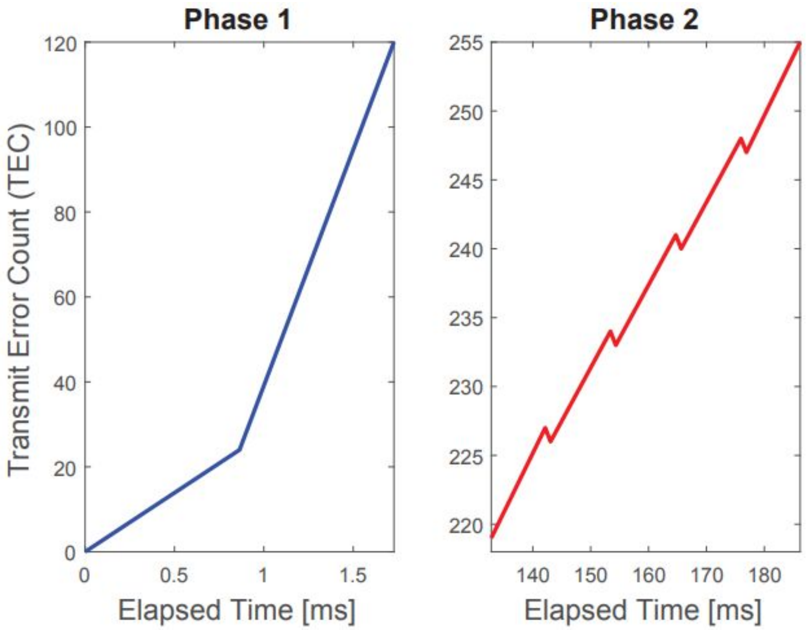


(c) Phase 2 – Victim in error-passive mode.

- TEC of victim and attacker differ

TECs Behavior





- 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

Preceded ID

- 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