# Lab - 02

## Getting Started with CAN-Bus

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The Controller Area Network (CAN) protocol was officially released in 1986 with the aim of reducing the length of cabling in a vehicle, thereby reducing cost and weight. In 1991, this goal was achieved and the first car with this serial communication bus went into production. Since then, the CAN bus has been standardised in two versions, high-speed CAN and low-speed/fault tolerant CAN. This leads to a lot of applications where CAN bus is used in our world such as vehicles, industrial automation, lifts, medical instruments and many more. This exercise is about implementing two UART-CAN gateways (implemented with the MCU board and the CAN adapter). Messages will be sent to the gateway using UART and transmitted from the gateway to the remote device via CAN. Data is exchanged between the devices using high-speed CAN.

### Objectives

- UART communication
- CAN bus initialization, configuration and implementation
- Design of a UART-CAN bi-directional gateway using the STM32 MCU

### Outcomes

- Understanding the use of CAN filters
- Understand the CAN address system
- Understanding the difference between high-speed and low-speed CAN bus
- Benefits of a stuff bit
- Using CAN to send and receive messages
- Using the STM32 as a gateway device between CAN and UART
- Using UART to communicate with CAN

# Description

## CAN bus history

Development of the Controller Area Network (CAN) began at Robert Bosch GmbH in 1983. The protocol was officially released in 1986 at the Society of Automotive Engineers (SAE) conference in Detroit, Michigan. The first CAN controller chips were introduced by Intel in 1987, followed shortly thereafter by Philips. The aim of this serial communication was to reduce the length of wiring in a vehicle, thereby reducing cost and weight. The Mercedes-Benz W140, launched in 1991, was the first production car to use a CAN-based bus system.

## CAN bus applications

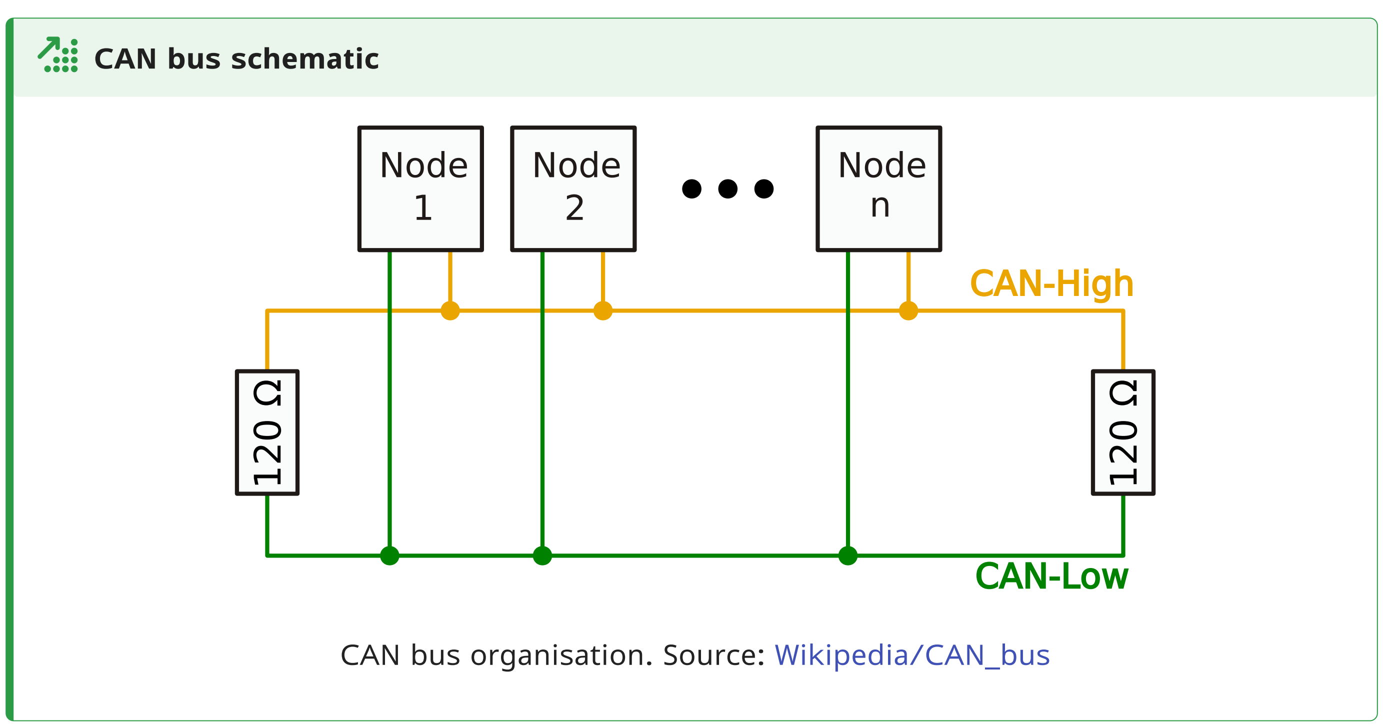
CAN is used as a communication method in many applications today:

- Passenger vehicles, trucks, buses
- Agricultural equipment
- Electronic equipment for aviation and navigation
- Industrial automation and mechanical control
- Elevators, escalators
- Building automation
- Medical instruments and equipment
- Model railways
- Ships and other maritime applications
- Lighting control systems

## CAN bus organization

CAN is a digital multi-master asynchronous serial bus. The participants are called nodes. All nodes are connected by a differential bus signal. The bus is a pair of wires with an impedance of $120\,\Omega$.

**CAN bus schematic**




CAN bus organisation. Source: Wikipedia/CAN_bus

Line terminations are required in a CAN bus system because CAN communication flows are bidirectional. The termination at each end absorbs the CAN signal energy and ensures that it is not reflected from the cable ends. Such reflections would cause interference, resulting in a degradation of the signal quality (reduction of **S**ignal **N**oise **R**atio SNR). The reflection will increase the bit error rate and the demand for low bit rates to ensure error-free transmission. Therefore, proper termination is a challenge in larger CAN networks.

**See also**

For more information on the terminating resistor, see also here

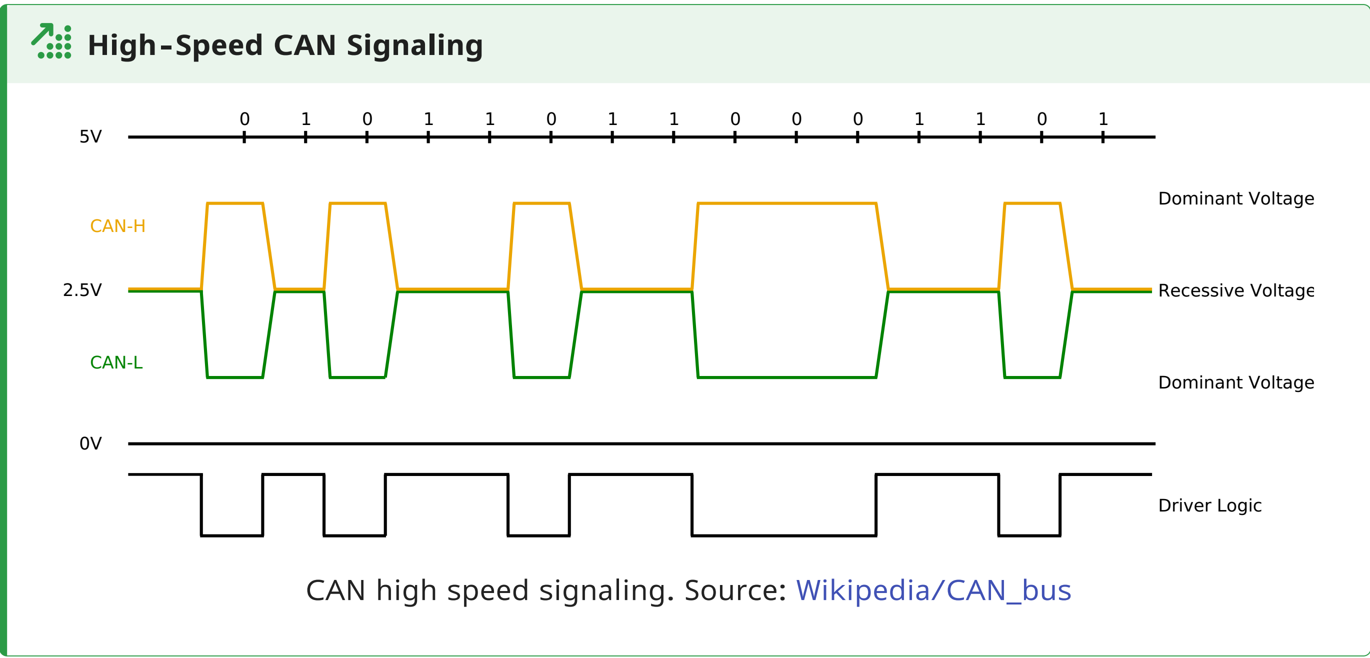
## Physical bus organisation

In 1993, the International Organisation for Standardisation (ISO) published the CAN standard ISO-11898. This specification consists of four parts. The first part, ISO-11898-1, contains the standard protocol. The second part is ISO-11898-2, also known as High-speed CAN, which defines the voltage levels of the signal.

**See also**

ISO publications of protocol ISO-11898-1 and high-speed ISO-11898-2

**High-Speed CAN Signaling**




CAN high speed signaling. Source: Wikipedia/CAN_bus

To transmit a logical 1, the two wires have the same voltage of $2.5\,\mathrm{V}$. To transmit a logical 0, however, the voltage levels change. The voltage of the CAN high wire is raised to $3.5\,\mathrm{V}$ and the CAN low wire is lowered to $1.5\,\mathrm{V}$. This makes the CAN bus very robust to signal interference. Like the UART, the CAN bus is an asynchronous transfer mode, which does not carry a clock. This means that a baud rate must

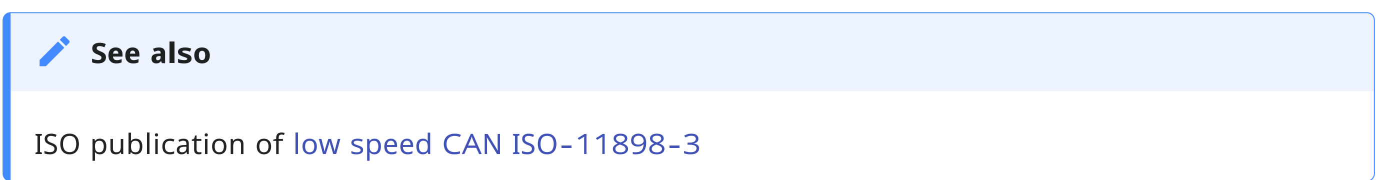
be agreed at which the data will be transmitted. The maximum speed depends on the length of the cable. Typical values are listed in the bitrate to distance table.

**Table bitrate vs. distance**

Bitrate to Distance

| **bitrate** / kbit/s | 10 | 20 | 50 | 125 | 250 | 500 | 1000 |
|---|---|---|---|---|---|---|---|
| **distance** | $6.7\,\mathrm{km}$ | $3.3\,\mathrm{km}$ | $1.0\,\mathrm{km}$ | $500\,\mathrm{m}$ | $250\,\mathrm{m}$ | $125\,\mathrm{m}$ | $25\,\mathrm{m}$ |

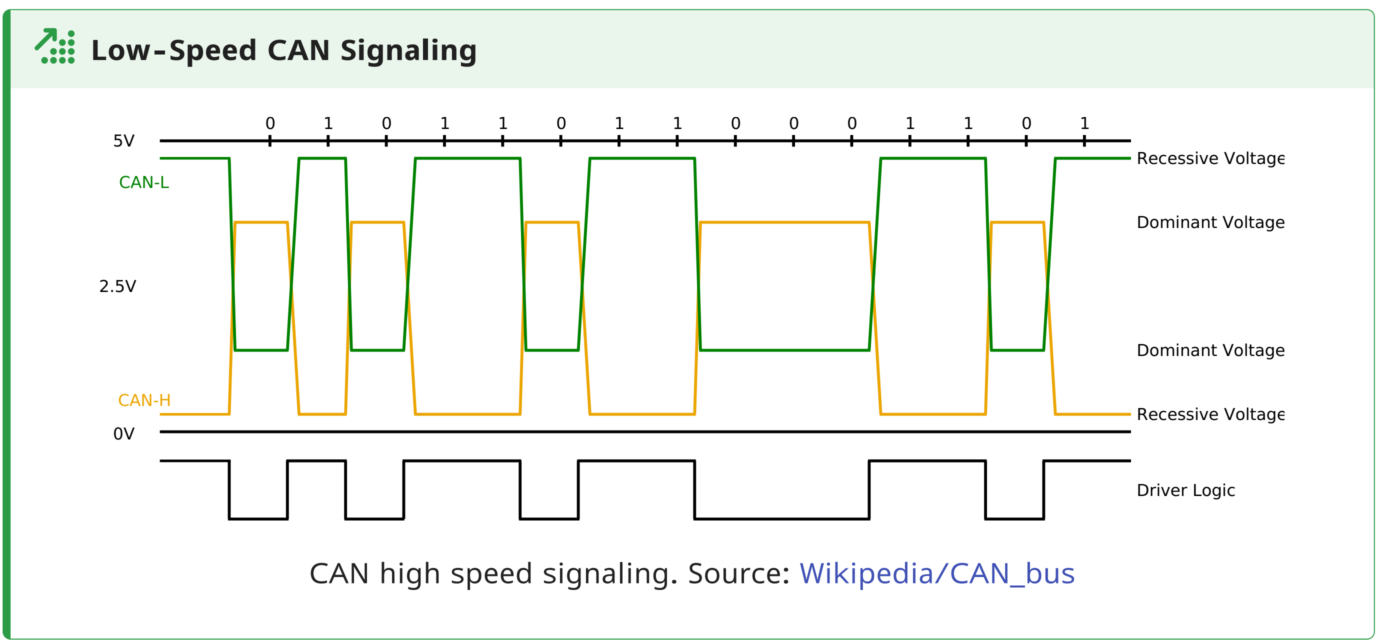
For optimal results, the CAN bus termination should match the nominal impedance of the cables, which for this standard is specified as $120\,\Omega$. Therefore $120\,\Omega$ termination adapters are considered the standard for CAN bus. Today there is another variant of the CAN bus, the ISO-11898-3, also called low-speed or fault-tolerant CAN.



**See also**

ISO publication of low speed CAN ISO-11898-3

**Low-Speed CAN Signaling**




CAN high speed signaling. Source: Wikipedia/CAN_bus

CAN bus signalling works in a similar way to the ISO standards mentioned above. The differences are in the voltage levels of the dominant and recessive states, as shown in Figure Low-Speed CAN Signaling. The advantage of this configuration is a higher voltage difference between the two lines and the logic voltage states. The recessive state between CAN-Low and CAN-High produces a negative voltage, while the dominant state produces a positive voltage. This makes the signalling more reliable and resistant to noise, but slower. The bit rate of these systems is limited from $5\,\mathrm{kbit/s}$ to only $125\,\mathrm{kbit/s}$. Another

difference is the termination resistor; low-speed CAN uses resistors at each node. The total termination resistor should be close to, but not less than $100\,\Omega$.

**See also**

For more information on CAN, see the can-bus-grundlagen page.

## CAN protocol

Both voltage level configurations use the same protocol for data transfer. Do an internet search and answer the following questions about the frame format:

**Question**

a. How many frame sizes are standardised?

b. What is a stuff bit and why is it used?

c. How many bytes of data can be sent in a data frame?

**Solution**

a. Two frame formats are standardised for the CAN bus. They differ in the identifier size:

   - Basic frame format with 11 identifier bits
   - Extended frame format with 29 identifier bits

   **See also**

   Source: https://en.wikipedia.org/wiki/CAN_bus#Data_frame

b. To ensure sufficient transitions to maintain synchronisation, a bit of opposite polarity is inserted after five consecutive bits of the same polarity. Example: 11111 **0** or 00000 **1**

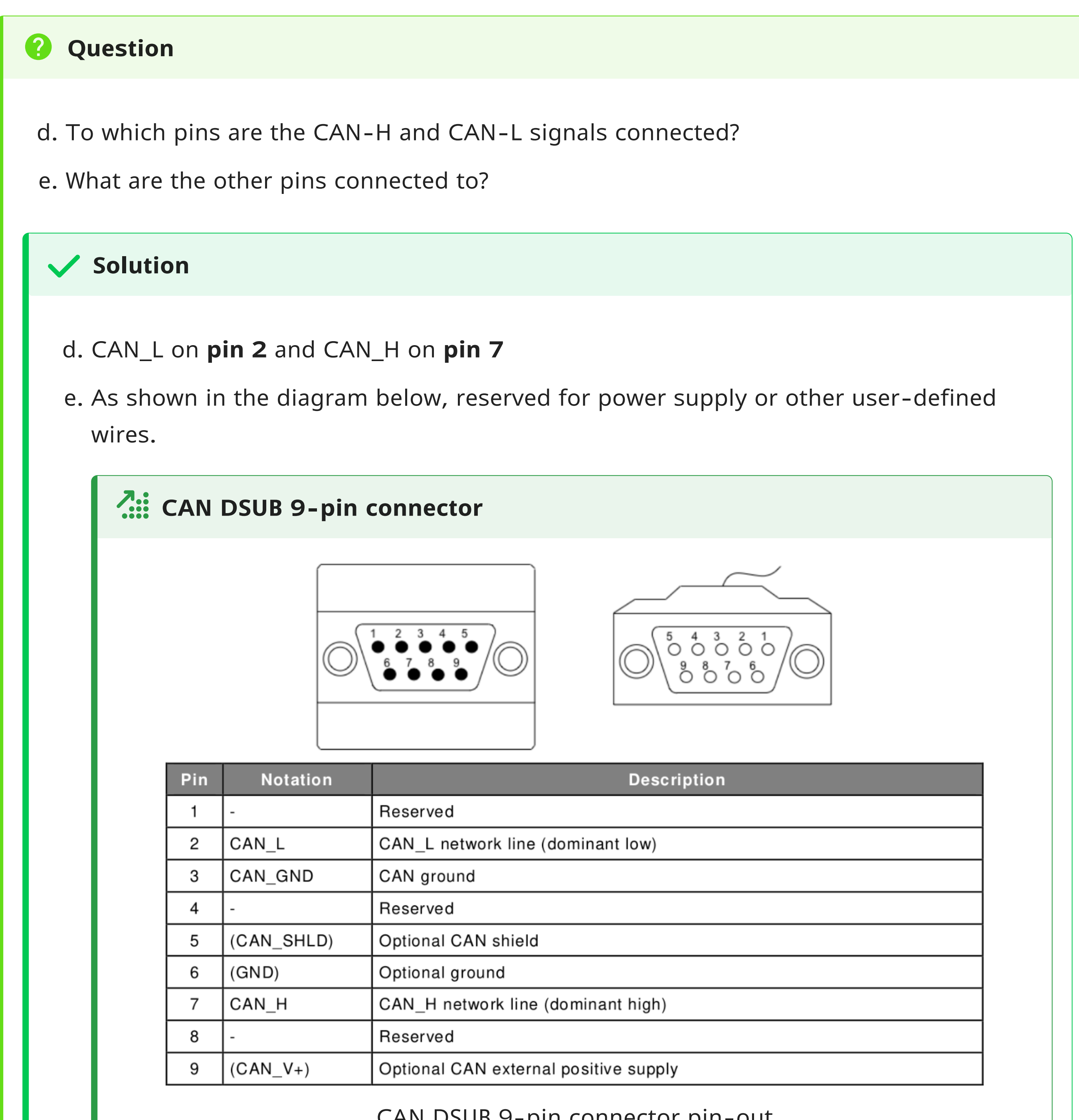
   **See also**

   Source: https://en.wikipedia.org/wiki/CAN_bus#Bit_stuffing

c. **8 bytes** can be sent in one frame.

## D-Sub plug

Although CAN would use only two wires plus generally a power and ground wire, it is common to use the D-Sub 9 connector. Find the answer to the following questions about the pinout of a D-Sub 9 connector with CAN bus:



**Question**

d. To which pins are the CAN-H and CAN-L signals connected?

e. What are the other pins connected to?

**Solution**

d. CAN_L on **pin 2** and CAN_H on **pin 7**

e. As shown in the diagram below, reserved for power supply or other user-defined wires.

**CAN DSUB 9-pin connector**



| Pin | Notation | Description |
|---|---|---|
| 1 | - | Reserved |
| 2 | CAN_L | CAN_L network line (dominant low) |
| 3 | CAN_GND | CAN ground |
| 4 | - | Reserved |
| 5 | (CAN_SHLD) | Optional CAN shield |
| 6 | (GND) | Optional ground |
| 7 | CAN_H | CAN_H network line (dominant high) |
| 8 | - | Reserved |
| 9 | (CAN_V+) | Optional CAN external positive supply |

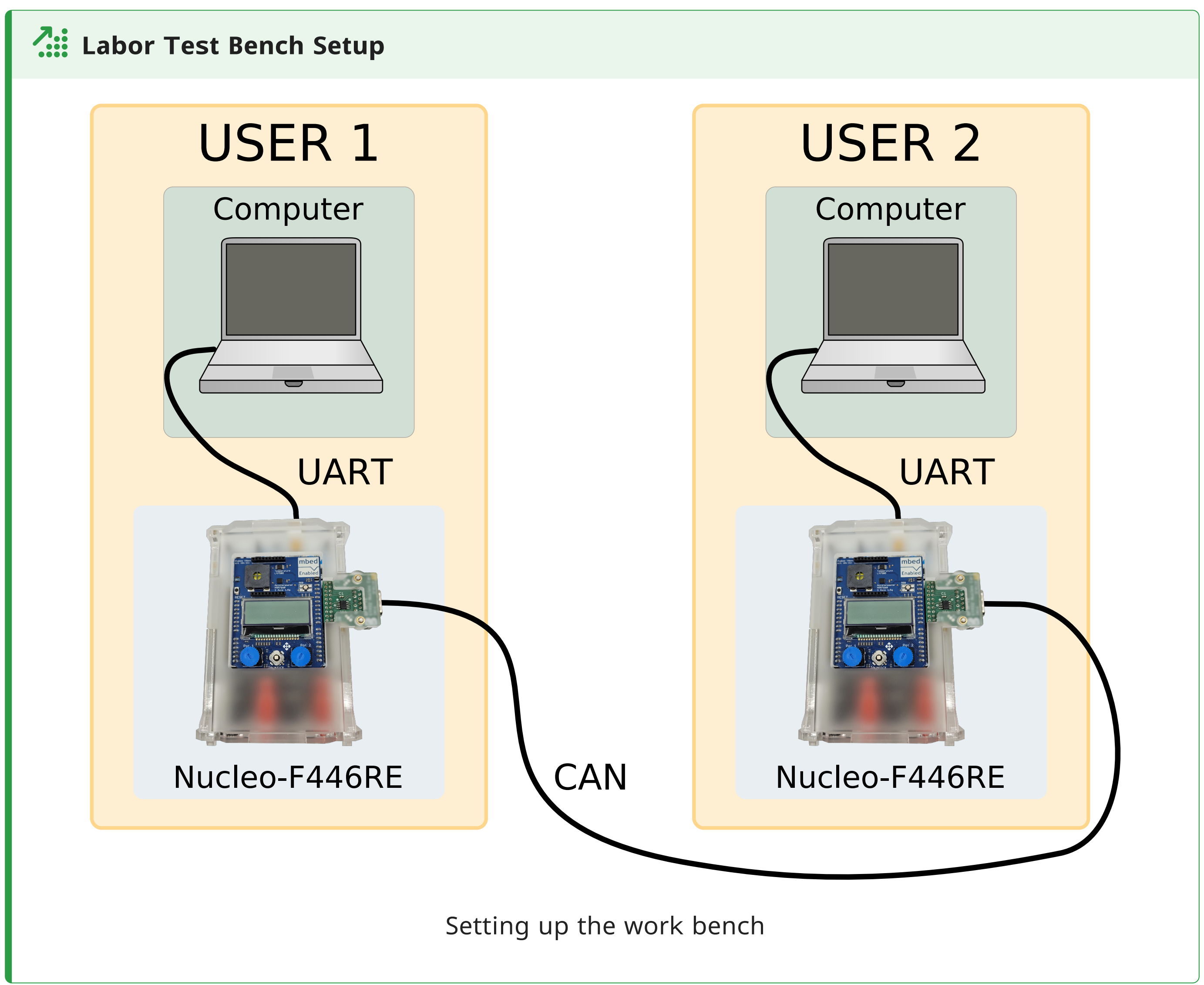
CAN DSUB 9-pin connector pin-out

## Tasks

You will design and implement a high speed CAN bus ⇔ UART adapter using the nucleo-F446RE and the CAN bus adapter from the BFH. The aim is to send data via the UART from the computer to the

controller. The controller then parses the received message. After parsing, the message is sent over the CAN bus to the desired destination (target device). Finally, the receiving node transmits the message via UART to the computer.

**Labor Test Bench Setup**




Setting up the work bench

To achieve the goal, you need to work in tandem. One member of the team is User 1 and the other is User 2, as shown in the figure work bench setup.

## UART communication

Before working through the CAN tasks, we start with the UART for communication between your microcontroller and the computer. This is used to handle CAN messages and CAN settings, and the appropriate commands must be defined. For our application at least the following methods are required.

UART Message commands

| Command | Arguments | Description |
| --- | --- | --- |
| getAddress | None | Get the current CAN address (filter value) of your gateway device |
| setAddress | address | Set the CAN address (filter) of your gateway device |
| sendMessage | target address, message | Send a CAN message with the specified message ID (address) |

## CAN configuration

Before the lab exercises can be carried out, questions about various CAN bus settings need to be answered. The aim is to configure the CAN bus to operate in high-speed mode with a speed of $1\,\mathrm{Mbit/s}$. To use CAN with the MCU, an adapter is required to set the correct voltage levels. Use the Nucleo-64 schematic and STM32 Nucleo CAN Adapter schematic to find the used GPIO pins and CAN peripheral.

**Question**

f. To which GPIO pins are CAN_H and CAN_L connected?

g. Which CAN peripheral is used for these pins?

**Solution**

f. CAN_TX on PA12 and CAN_RX on PA11

g. The CAN IP **CAN1** is used

The CAN peripheral can be configured by reading the sample point of a bit. Read in the reference manual RM0390 on page 1063 how to get the nominal bit time and how to derive the desired baud rate from $1\,\mathrm{Mbit/s}$. The same figure describes how the nominal bit time is divided. There are three segments involved. The SYNC_SEC is the synchronisation segment and defines the duration of a time quantum. Bit segments 1 and 2 (BS1 and BS2) are used to define the sampling time. At this time, the CAN bus circuit checks the input voltage values. Their perfect position can be studied in more detail in the scientific publication referenced below. Special attention is given to the CAN bus consistency check:

- The tested baud rate sampling point adapts to the range of 60%-80%, and the characteristic value is 70%.

With this information, the register values can be set to the correct values to achieve the bit rate of $1\,\mathrm{Mbit/s}$.

**See also**

The publication can be found at Research on CAN bus consistency test method. You can also find more information about signal edge time, signal delay and bus utilisation.

**Question**

h. What is the formula for the sample point?

i. What is the nominalBitTime for $1\,\mathrm{Mbit/s}$?

j. How would you set BS1 and BS2 for a time quantum of 100ns?

**Solution**

h. $\mathrm{SAMPLE\ POINT} = \frac{1+BS_1}{1+BS_1+BS_2}$

i. $1\,\mu s$

j. $0,7 = \frac{1+\mathrm{BS1}}{1+\mathrm{BS1}+\mathrm{BS2}} \rightarrow \mathrm{BS1} = 6, \mathrm{BS2} = 3$

**Calculation path**

$\mathrm{Baudrate} = 1'000'000\,\mathrm{bd}$

$\mathrm{nominal\ bit\ time} = \frac{1}{\mathrm{Baudrate}} = \frac{1}{10^6} = 1\,\mu s = 1 * t_q + BS_1 * t_q + BS_2 * t_q$

From exercise description:

$t_q = \frac{PSC}{F_{APB1}} = 0.1\mu s$

$1\,\mu s = t_q + BS_1 * t_q + BS_2 * t_q = t_q * (1 + BS_1 + BS_2)$

$1\mu s = 0.1\mu s * (1 + BS_1 + BS_2)$

$10 = 1 + BS_1 + BS_2$

$9 = BS_1 + BS_2 \rightarrow BS_2 = 9 - BS_1$

With defined 70% as sample point:

$0,7 = \frac{1+BS_1}{1+BS_1+BS_2} = \frac{1+BS_1}{1+BS_1+9-BS_1} = \frac{1+BS_1}{10}$

$1 + BS_1 = 7 \rightarrow BS_1 = 6$

$BS_2 = 9 - BS_1 = 9 - 6 = 3$

# Implementation

## Project initialisation

Before using CAN in this exercise, check that the project compilation and UART communication are working as expected. Start a new standard project or use a previous exercise as a template.

**Project setup and UART communication**

1. Create a new STM32CubeMX project with default configuration.
2. Add a method to receive a message with UART without polling. You can echo the received message back to the host as a test.
3. Parse the received message with your communication concept. Your concept should at least understand the commands discussed above.
4. Test your commands using the debugger.

## CAN bus

The CAN configuration is not as easy to configure as the UART. It has more properties that you will need to parameterise. The aim is to configure the CAN bus to operate in high-speed mode at a speed of $1\,\mathrm{Mbit/s}$.

**CAN-Bus initialisation in STM32CubeMX**

5. Enable the correct peripheral and GPIO pins as discussed in the tasks section.
6. Set the prescaler and the two TimeSeg1 and TimeSeg2 (time quanta bit segment 1 and 2 in the STM32 CubeMX application or the initialisation object) to set the sample point to 70% and a bitrate of $1\,\mathrm{Mbit/s}$.
7. Set the operating mode to `Normal` and ReSynchronization Jump With to 1.

**Tip**

To test your CAN bus configuration without a colleague, change the operating mode to `Loopback`. This combines receiving with sending and your application can read the CAN message sent. Other devices can also read your message, but your device can no longer receive messages from other devices!

8. Deactivate all other parameters.
9. To receive messages, the interrupt on the buffer FIFO 0 will be used. Enable for this the interrupt on `CAN1 RX0`.

10. Generate code and close STM32CubeMX.

After initialisation, the CAN bus cannot yet receive or send messages. To receive a message, CAN uses a filter to check if the message is addressed to the device.

**Setup CAN-Bus filter**

11. Create a new module with header and source files for CAN bus handling.
12. Read the doxygen documentation from the `CAN_FilterTypeDef`.
13. Create a new function prototype to set a CAN bus filter. Take the CAN_HandleTypeDef, the gateway address and the filter bank (can be a constant) as arguments.

**setFilter function prototype**

```
HAL_StatusTypeDef canbus_setFilter(
   CAN_HandleTypeDef *hcan,
   uint32_t gatewayAddress,
   uint32_t filterBank);
```

14. Implement the new function:

    1. Create a new `CAN_FilterTypeDef` instance for configuration.
    2. Configure the filter instance.

       Configure it according to the following guideline:

       - FilterIdHigh

         Set the desired CAN node gateway address. As this is an 11-bit value, shift the address so that the MSB is at position 15.

       - FilterIdLow

         Set to zero as it is not used yet.

       - FilterMaskIdHigh

         Set to `0xFFFF` to enable the mask on each bit, resulting in a “must match”. See RM0390 on page 1056 for more information.

       - FilterMaskIdLow

         Set to the same value as FilterIdLow.

       - FilterFIFOAssignment

         Expected to be `CAN_FILTER_FIFO0` or `CAN_FILTER_FIFO1`. Use FIFO0 as the interrupt is used for this buffer.

- FilterBank

  Use an argument value or constant for a number between the possible ranges described in the Doxygen documentation.

- FilterMode

  Since we only want to set one address, use `CAN_FILTERMODE_IDMASK` and not `CAN_FILTERMODE_IDLIST`.

- FilterScale

  Use the `CAN_FILTERSCALE_32BIT` scale.

- FilterActivation

  Enable the CAN filter with the `CAN_FILTER_ENABLE` flag.

- SlaveStartFilterBank

  We use a single CAN instance. Read the doxygen comment for SlaveStartFilterBank for more information.

3. Register the filter with the CAN instance by calling the function `HAL_CAN_ConfigFilter()`.

By activating the previously configured filter, the CAN bus is able to receive messages for the configured address. As we have activated the interrupt mode on RX0, you can use the callback function of HAL. The zero of RX0 refers to the first FIFO buffer (index 0 → FIFO0). The callback function has the following prototype: void HAL_CAN_RxFifo0MsgPendingCallback(CAN_HandleTypeDef *hcan).

**CAN RX FIFO0 Callback implementation**

15. Write the function definition for the `HAL_CAN_RxFifo0MsgPendingCallback()`.
16. Study the function `HAL_CAN_GetRxMessage()` including the argument `CAN_RxHeaderTypeDef()`.
17. Implement a handler to receive messages from CAN. Remember on how to use UART with receiving messages.
18. Use the above function to get the data received from the CAN bus.

**Hint**

Before calling the function, create an instance of the `CAN_RxHeaderTypeDef()` structure and pass it as a reference.

19. Store the current length in your receive message handler. The length is stored in the RXHeader structure in the DLC member.

To send a message, HAL provides a similar interface and methods to those described above for receiving. The aim is to implement a function in the CAN bus module to send any message. The function is needed to configure the `CAN_TxHeaderTypeDef()` correctly.

**Implement a CAN transmit function**

20. Add a new function declaration to your CAN bus module:

**Question**

a. What do you need as arguments for this function?

**Solution**

a. This function requires at least the following arguments:

- `CAN_HandleTypeDef* hcan`, reference to the CAN handler instance
- `char* data`, the message to send, can also be a `uint8_t`
- `uint32_t targetAddress`, the address of the target device

21. Create an instance of a `CAN_TxHeaderTypeDef()` structure.

22. Unlike the receive function, you must assign the values to the structure for the send function to work. Follow the instructions below:

- StdId

  Set the address of your destination.

- ExtId

  The extended form of the address. This is unused as we will use the standard form from above.

- IDE

  Set `CAN_ID_STD` or `CAN_ID_EXT`. We use the standard (STD) form with 11 identifier bits.

- RTR

  Set `CAN_RTR_DATA` to send a data frame.

- DLC

  Set the number of data bytes to send. See the possible range in the Doxygen documentation from DLC.

- TransmitGlobalTime

Disable transmission of the global time to be sent with byte 6 and byte 7.

23. Create the possibility to send messages.
24. Finally call the HAL function `HAL_CAN_AddTxMessage()` to transmit the data bytes. Pass an empty `uint32_t` variable as the mailbox argument.

When everything is ready for testing, set up a test implementation to send and receive some messages from your colleague.

**Test CAN communication**

25. Transmit the received CAN messages to your computer via UART.
26. Set a fixed CAN address for your gateway. Make sure that your colleague does not have the same address as you.
27. Start the CAN peripheral with the function `HAL_CAN_Start()`.
28. Activate the CAN bus receive interrupt using the `HAL_CAN_ActivateNotification()` function. Enable it for the receive FIFO0 interrupt. You can use the macro `CAN_IT_RX_FIFO0_MSG_PENDING`. Put it in your main function.
29. Use CAN to send a constant message to your colleague every second.
30. Connect two boards with a cable and send some test messages.

**Hint**

Do not forget to connect the terminating resistors.

## CAN gateway

Now that you know that the UART and CAN bus work, connect the two peripherals together. Implement the gateway using the code you have written. You can use most of the code directly, only small adjustments are required.

**Implementation of CAN gateway**

31. Process the `setAddress` command with your `setFilter()` method.
32. Return the current address of your filterBank (given as an argument or constant in your `setFilter()` method) with `getAddress`.

> **Hint**
>
> One solution to this problem is to access the filter bank register directly and return the current stored address. The register would be the Filter bank i register found in the RM0390 on page 1085. You can access the filter bank using the CMSIS library. CAN has a member `sFilterRegister` where you can access the filter bank and the corresponding stored address.

33. Extend your CAN send function to send data longer than a CAN data frame.
34. Use the `sendMessage` command to transmit the message to the defined destination address from the arguments via CAN.
35. Test your implementation with your colleague.