Open source implementation of ECSS-CAN Bus Extension Protocol for CubeSats

CAN in Space workshop
14-16 June 2017 at SITAEL, Moli di Bari, Italy
Artur Scholz, Visionspace Technologies GmbH

Motivation

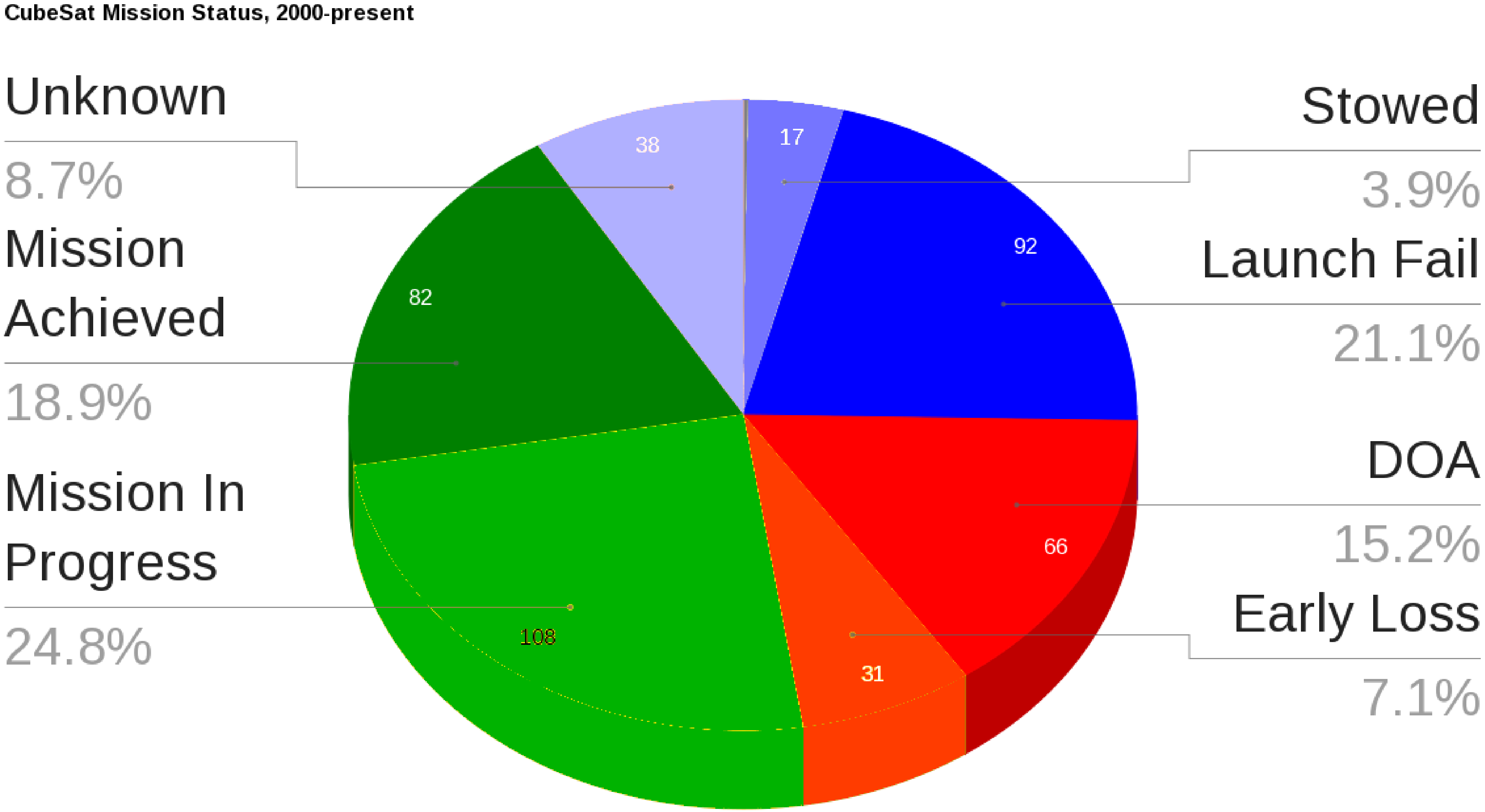


Chart created Oct 2016 using data from M. Swartwout
https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database

Overview

- CubeSats are lacking a space-grade command and control bus

- Traffic is moderate but most be utmost reliable and real-time
- Implementable in low-cost, constrained microcontroller
- Bus interaction should be simple and practical

Bus candidates

- MIL-STD-1553
- UART
- SPI
- I2C
- USB
- SpaceWire
- CANBus Extension minimal implementation

ECSS-E-ST-50-15C minimal implementation for CubeSats

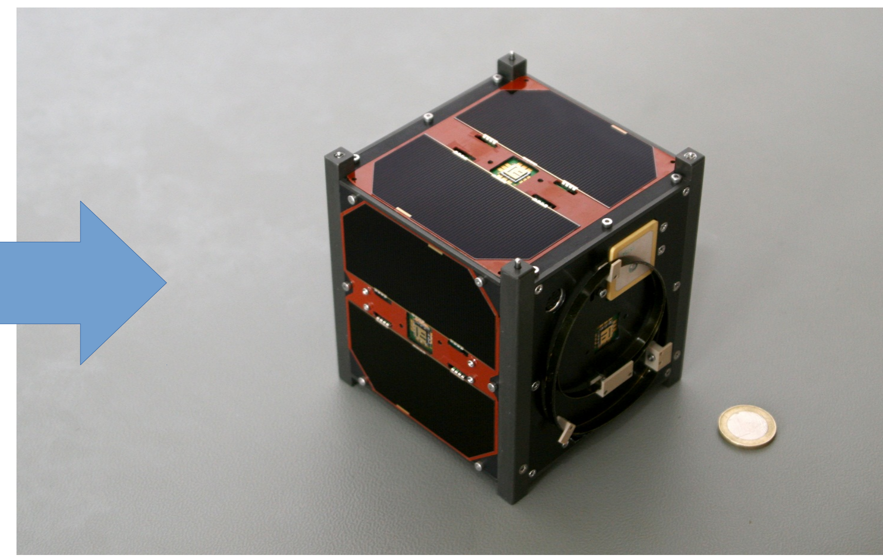
ECSS-E-ST-50-15C
1 May 2015

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

CANbus extension protocol

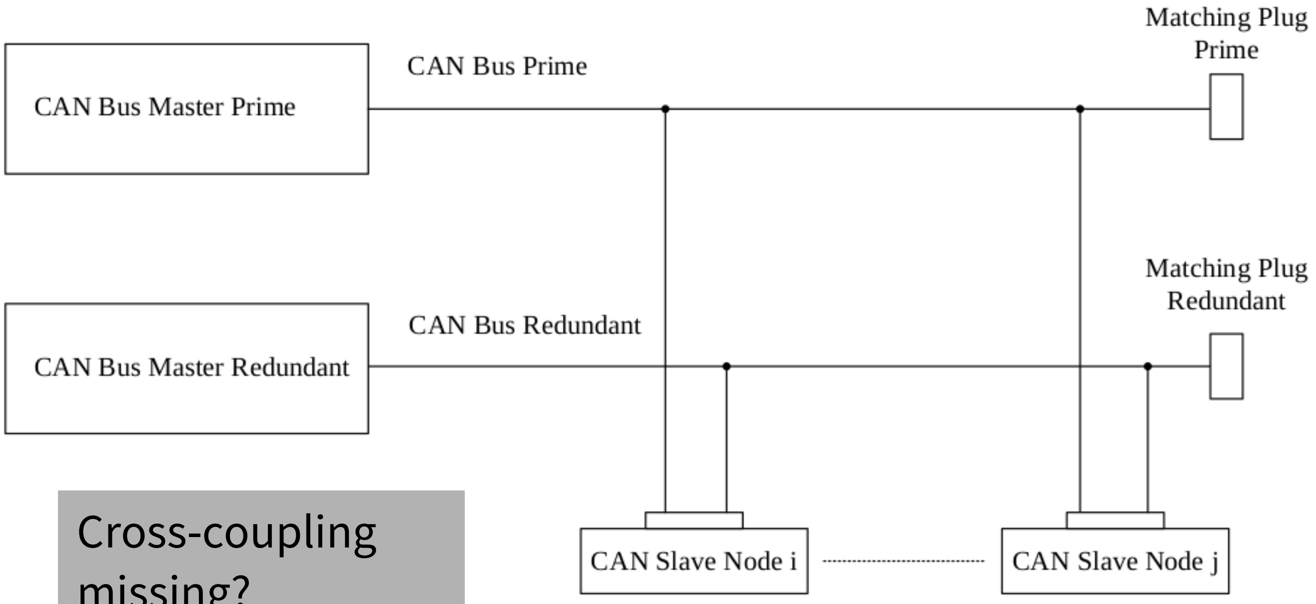
ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands



Communication model

4.5 Communication model

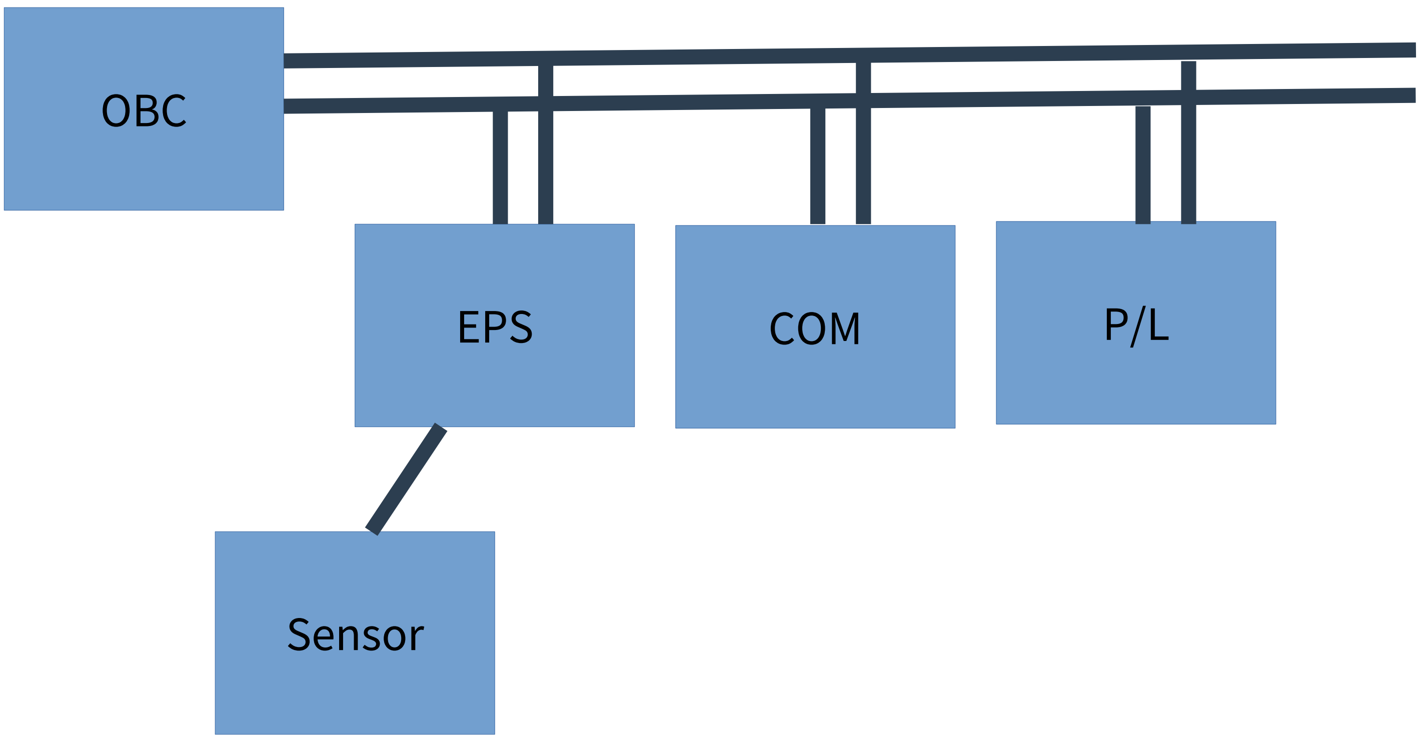
The communication model is based on a CAN Network master connected to up to 126 slave devices.



7 bit ID => 128 (0..127)
0 = broadcast (not used)
1 = master
2-127 = slave

Cross-coupling missing?

Communication model - CubeSat



Physical layer - topology

5.1.1.1 General

A spacecraft system using CAN Network shall use either of the following physical topologies:

1. A Linear multi-drop topology…

2. A Daisy chain topology...

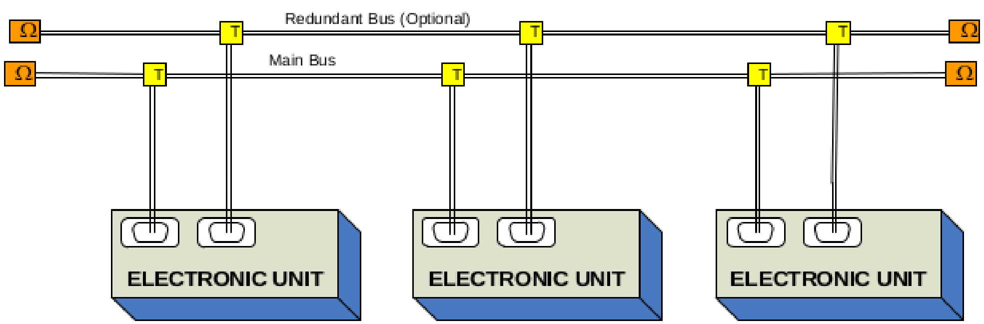


Figure 5-1: Linear multi-drop topology

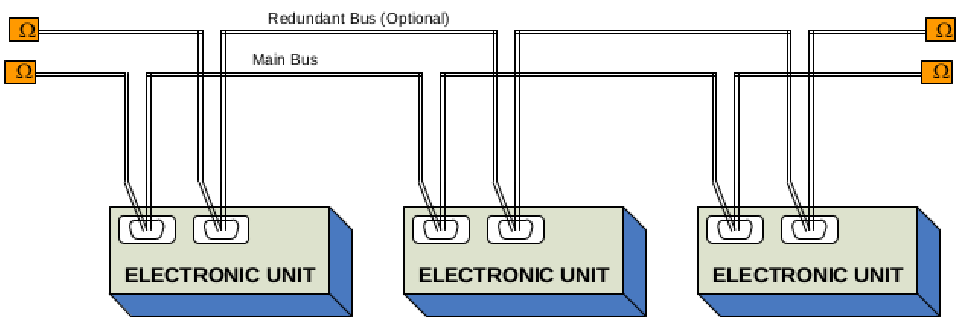
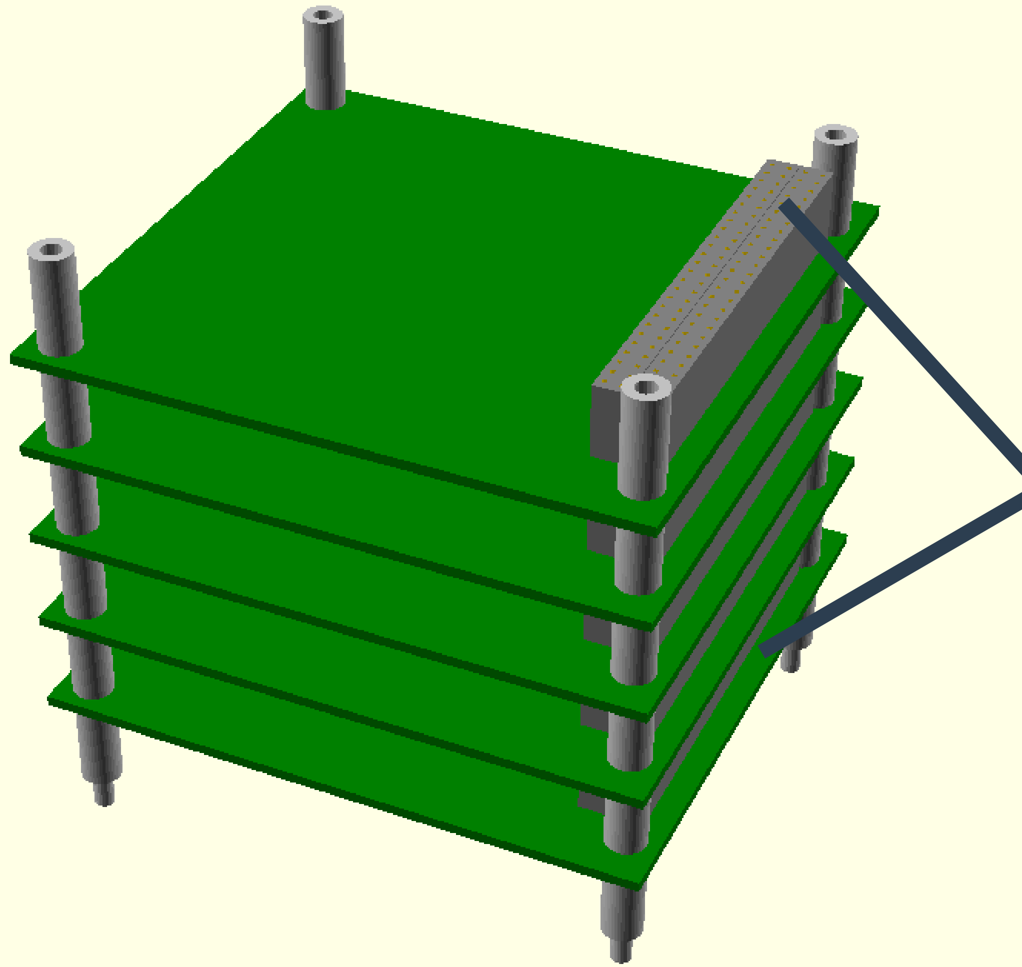


Figure 5-2: Daisy chain topology.

Physical layer – topology - CubeSat

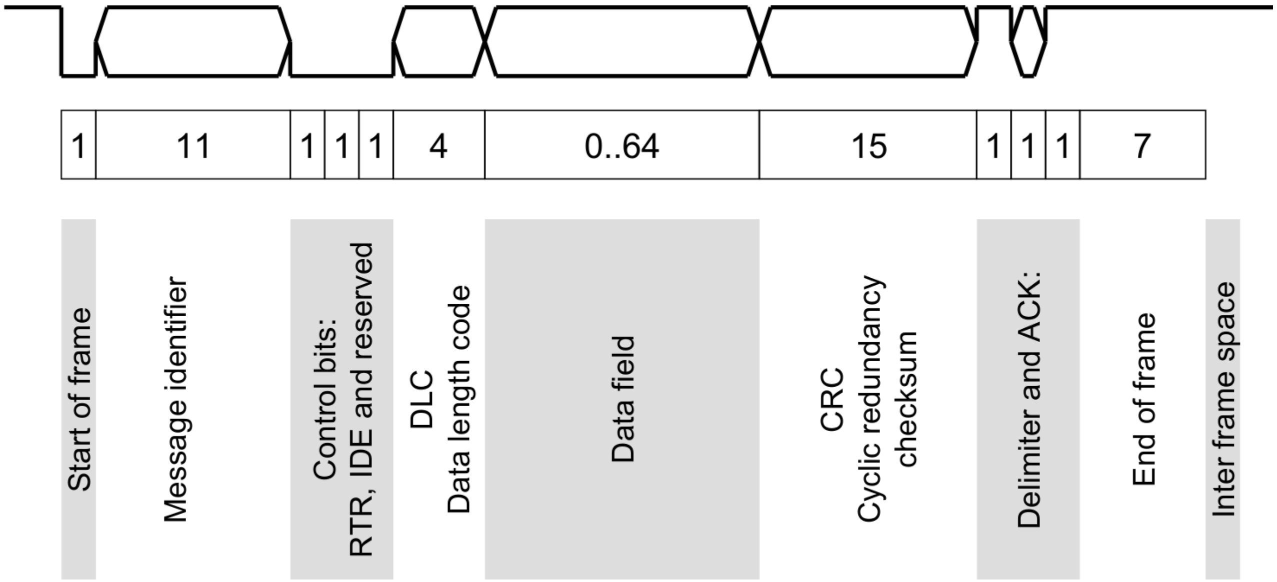
No cables
No connectors
Medium is copper tracks and pins



120 Ohm terminating resistor

Data link layer

- 11-bit CAN ID, no ID extension
- No RTR (remote transmission request)
- No remote and overload frame
- Only data frame and error frame



CANopen higher layer protocol

- **Service data objects**
- **Process data objects**
- **Synchronization object**
- **Emergency object**
- **Network management objects**
  - Module control services
  - Error control services
  - Bootup service
  - Node state diagram
- **Electronic data sheets**
- **Device and application profiles**
- **Object dictionary**

CANopen higher layer protocol

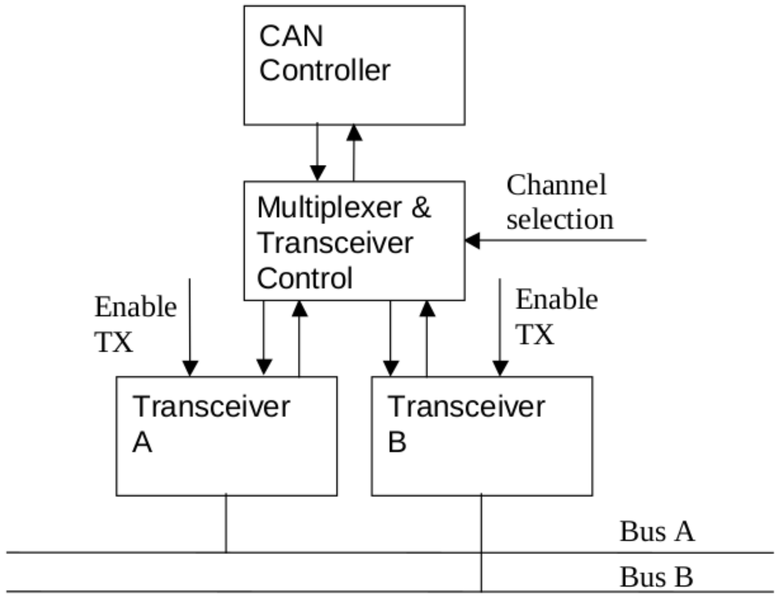
- ~~Service data objects~~
- **Process data objects - PDO**
- **Synchronization object - SYNC**
- ~~Emergency object~~
- **Network management objects**
  - ~~Module control services~~
  - Error control services - HB
  - ~~Bootup service~~
  - ~~Node state diagram~~
- ~~Electronic data sheets~~
- ~~Device and application profiles~~
- **Object dictionary - OD**

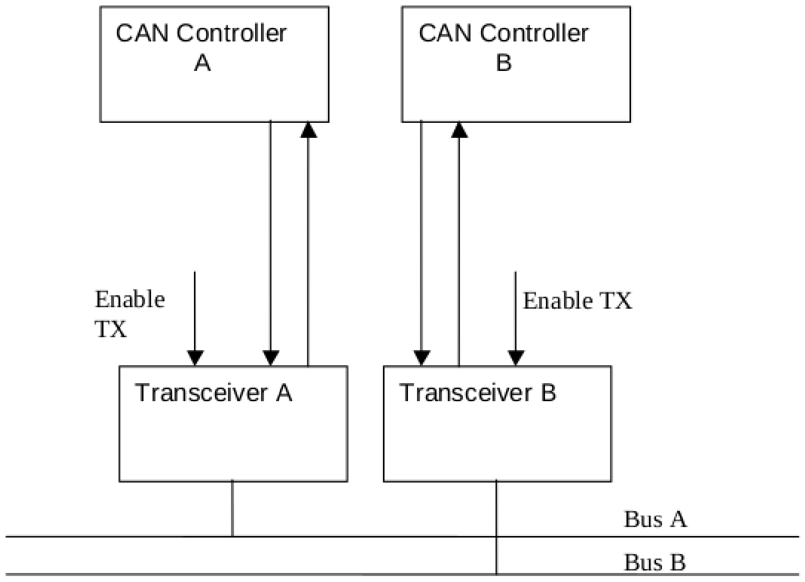
Minimal implementation

Redundancy management and monitoring

4.8.1 Overview

The selective bus access architecture allows communication on one bus at a time, whereas the parallel bus access architecture allows simultaneous communication on both a nominal and a redundant bus.





Redundancy management and monitoring

4.8.2 Node Monitoring via … Heartbeat Messages

...a node automatically transmits its communication state…

9.4.6.1 Module control services

Autonomous operations of slave nodes shall not be used.

6.5.2 Error control service

All slave nodes shall consume the redundancy master Heartbeat message.

4.8.3 Bus monitoring and reconfiguration management

The Redundancy Master defines the bus to be considered active by periodic transmission of CANopen Heartbeat messages on the active bus. The slave nodes monitor the presence of the Heartbeat message from the master to determine the active bus.

Redundancy management and monitoring

8.3.2 Start-up procedure

After a node power-on or after hardware reset, the node shall use the bus defined by the Bdefault parameter as the active bus.

9.4.9.2 Bootup service

Nodes shall not produce Bootup Service messages.

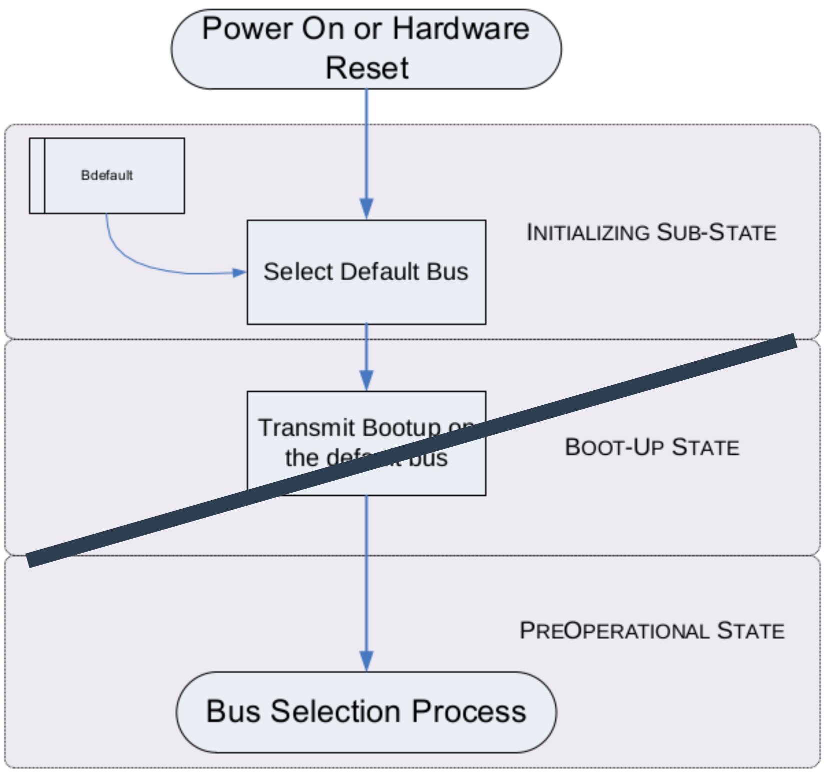


Figure 8-1: Node start up procedure

Redundancy management and monitoring

8.3.3 Bus monitoring protocol

The Redundancy Master shall periodically produce CANopen Master Heartbeat messages on the active bus.

The RM shall switch over and operate on the alternate bus by…:

1. Stopping transmission of HB messages on the active bus, and
2. Starting transmission of HB messages on the alternate bus

Each slave node shall be a consumer of the Master HB messages

Each slave node shall periodically transmit CANopen HB messages on the bus it considers being the active.

Redundancy management and monitoring

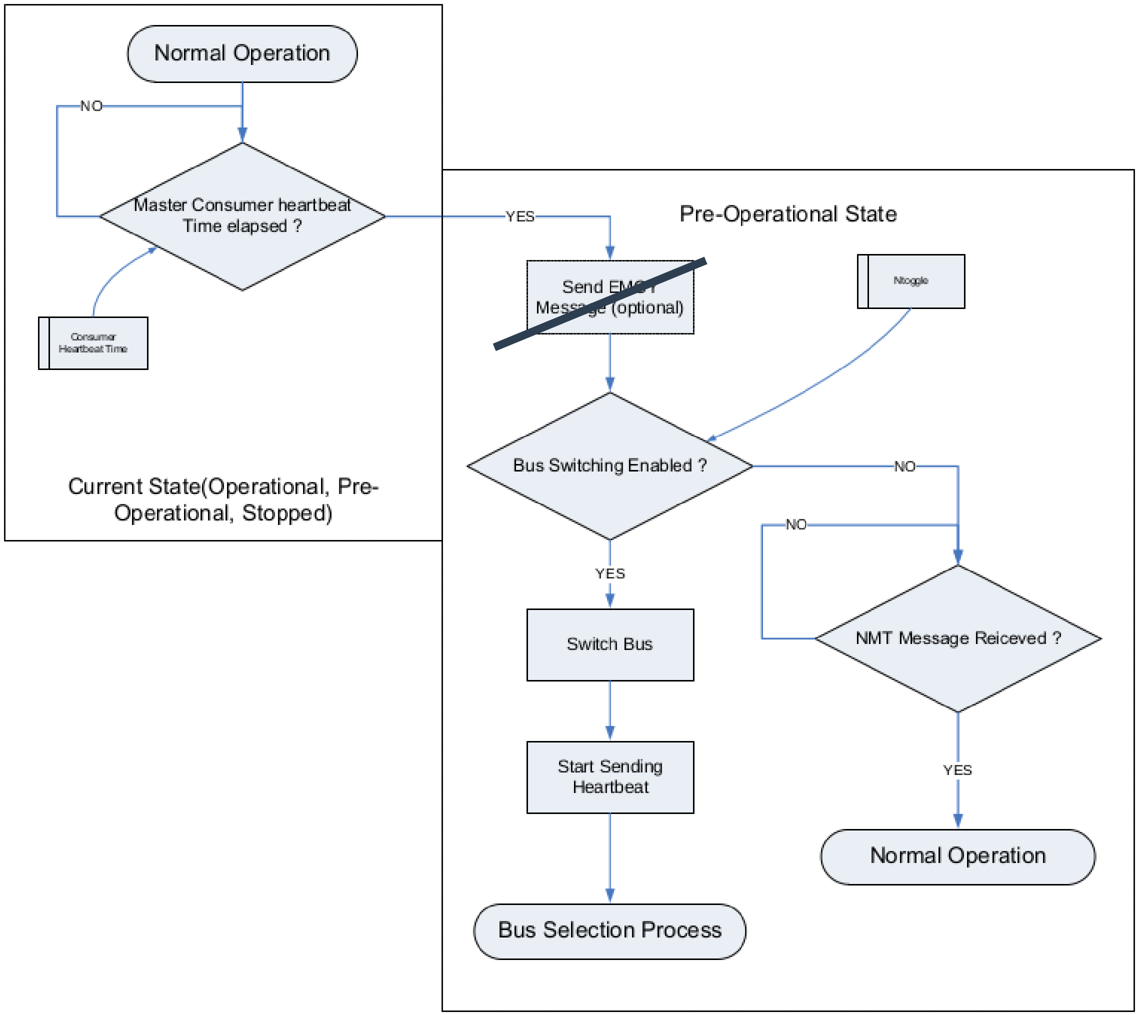


Figure 8-2: Bus monitoring logic

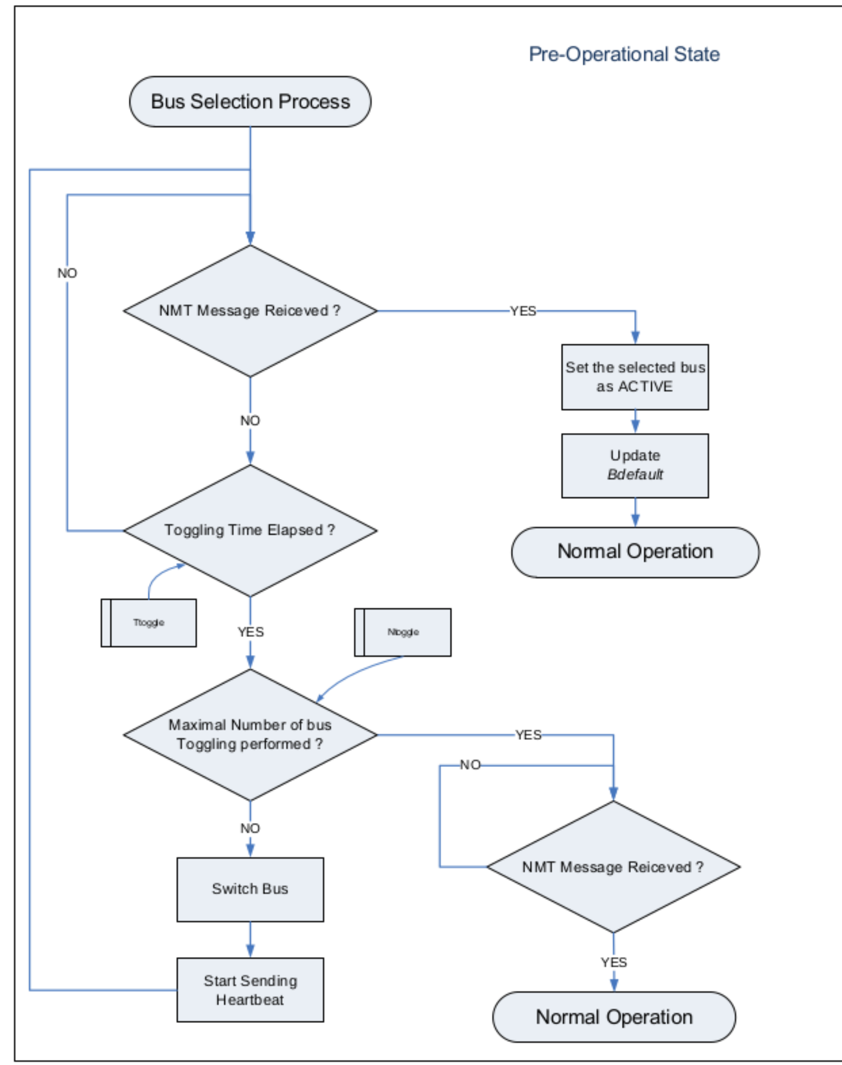


Figure 8-3: Slave bus selection process, toggling mechanism

Redundancy management and monitoring

Table 8-1: BUS redundancy management parameters for slaves

Parameter	Remark
Consumer Heartbeat Time Index: 1016h Subindex: 01h Data Type: Unsigned16 + Unsigned16 NodeID, HB Time in milliseconds	The Consumer Heartbeat Time parameter is specified by CANopen. The parameter specifies the maximum time allowed between two subsequent Heartbeat messages linked to that heartbeat consumer.
Producer Heartbeat Time Index: 1017h Subindex: 00h Data Type: Unsigned16 Unit: millisecond	The Producer Heartbeat Time parameter is specified by CANopen. The parameter specifies the maximum time allowed between two subsequent Heartbeat message transmissions.
Bdefault Index: 2000h Subindex: 01h Data Type: Unsigned8	Bdefault specifies the bus to be considered active after a node power-on, node hardware reset.
Ttoggle Index: 2000h Subindex: 02h Data Type: Unsigned8	Ttoggle specifies the number of Consumer Heartbeat times during which the node is required to be listening for an NMT HB message on a particular bus before switching to the other bus.
Ntoggle Index: 2000h Subindex: 03h Data Type: Unsigned8	Ntoggle specifies the number of toggles between the Nominal and Redundant bus in case of no HB message being detected. If an even number is used the last toggle puts the system into Bdefault.
Ctoggle Index: 2000h Subindex: 04h Data Type: Unsigned8	The counter of Ntoggles (bus toggles) shows the count of the number of toggles that have already been performed by the device.

Table 8-2: BUS redundancy management parameters for master

Parameter	Remark
Consumer Heartbeat Time Index: 1016h Subindex: one per slave node Data Type: Unsigned16 + Unsigned16 NodeID, HB Time in milliseconds	The Consumer Heartbeat Time parameter is specified by CANopen. The parameter specifies the maximum time allowed between two subsequent Heartbeat messages linked to that heartbeat consumer.
Producer Heartbeat Time Index: 1017h Subindex: 01h Data Type: Unsigned16 HB Time in milliseconds	The Producer Heartbeat Time parameter is specified by CANopen. The parameter specifies the maximum time allowed between two subsequent Heartbeat message transmissions.
Bdefault Index: 2000h Subindex: 01h Data Type: Unsigned8	Bdefault specifies the bus to be considered active after a master power-on or master hardware reset.
Ttoggle Index: 2000h Subindex: 02h Data Type: Unsigned8	Ttoggle specifies the number of Consumer Heartbeat times during which the node is required to be listening for an NMT HB message on a particular bus before switching to the other bus.
Ntoggle Index: 2000h Subindex: 03h Data Type: Unsigned8	Ntoggle specifies the number of toggles between the Nominal and Redundant bus in case of no HB message being detected. If an even number is used the last toggle puts the system into Bdefault.
Ctoggle Index: 2000h Subindex: 04h Data Type: Unsigned8	The counter of Ntoggles (bus toggles) shows the count of the number of toggles that have already been performed by the device.

Time distribution

7.1.1 Time code formats

Each device … that maintains time information shall use Spacecraft Elapsed Time (SCET)… The time code format .. is the CCSDS Unsegmented Time Code (CUC).

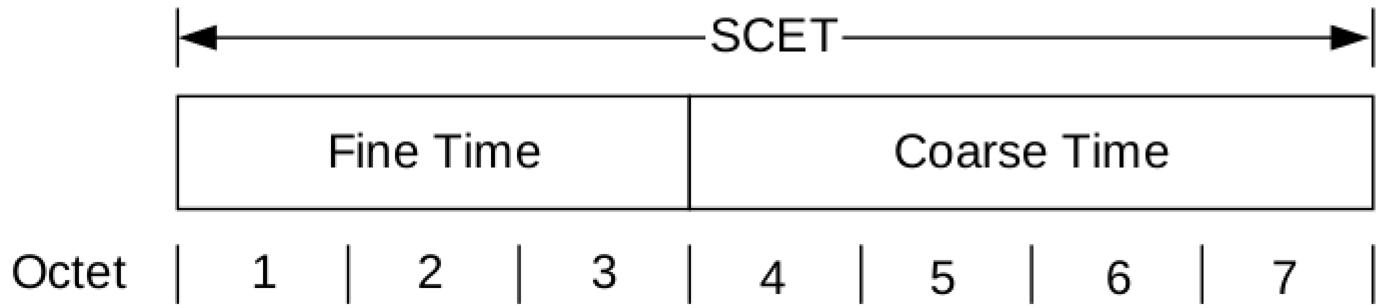


Figure 7-1: Format for objects containing the SCET

8bit fine time→ 100 ms = 100 * 256/1000 = 25.6 → 25

Time distribution

7.1.2 Spacecraft elapsed time objects

Each device (that maintains time information) shall implement one *Local SCET Set* and one *Local SCET Get* object in the Object Dictionary.

7.2.2 Time distribution protocol

The Time Producer shall map the Local SCET Get object to a dedicated *Spacecraft Time PDO* transmit PDO...to convey its local time to the time consumers… There shall be only one Spacecraft Time PDO in a particular system. The Time Consumers shall map the Local SCET Set objects to the Spacecraft Time PDO receive PDO.

Each time consumer shall map the *Local SCET Get* object … to a dedicated Local Time PDO...to convey its local time on the CAN Network.

Minimal implementation

9.2 Object dictionary

...it is acceptable that the CANopen objects...are hardcoded...

9.3 Minimal set CANopen objects

...only 4 Transmit and 4 Receive PDOs are implemented.

PDOs
PDO mappings
SYNC
HB

Table 9-1: Peer-to-Peer objects of the minimal set

Object	Function code (ID-bits 10-7)	COB-ID Calculation (hexa)	COB-ID Range identifier (hexa)	Communication parameters at OD index (hexa)
PDO 1 (transmit)	0011	180 + Node ID	181 - 1FF	1800
PDO 1 (receive)	0100	200 + Node ID	201 - 27F	1400
PDO 2 (transmit)	0101	280 + Node ID	281 - 2FF	1801
PDO 2 (receive)	0110	300 + Node ID	301 - 37F	1401
PDO 3 (transmit)	0111	380 + Node ID	381 - 3FF	1802
PDO 3 (receive)	1000	400 + Node ID	401 - 47F	1402
PDO 4 (transmit)	1001	480 + Node ID	481 - 4FF	1803
PDO 4 (receive)	1010	500 + Node ID	501 - 57F	1403
NMT *Error Control*	1110	700 + Node ID	701 - 77F	1016, 1017

Table 9-2: Broadcast objects of the minimal set

Object	Function code (ID-bits 10-7)	Resulting COB-IDs (hexa)	Communication parameters at OD Index (hexa)
SYNC	0001	80	1005, 1006, 1007

Minimal implementation

9.4.1 Minimal set protocol definitions

Communication between master and slave nodes shall be…

1. Transmission of configuration data or commands to a slave, is called unconfirmed command.
2. Start of a data transmission from slave is called telemetry request.

… data bytes shall contain the command itself… to identify the process to be performed by the slave.

Minimal implementation

1400h = RPDO1
281h = TPDO2 + id 1

1801h = TPDO2
281h = TPDO2 + id 1

0100 = RPDO1

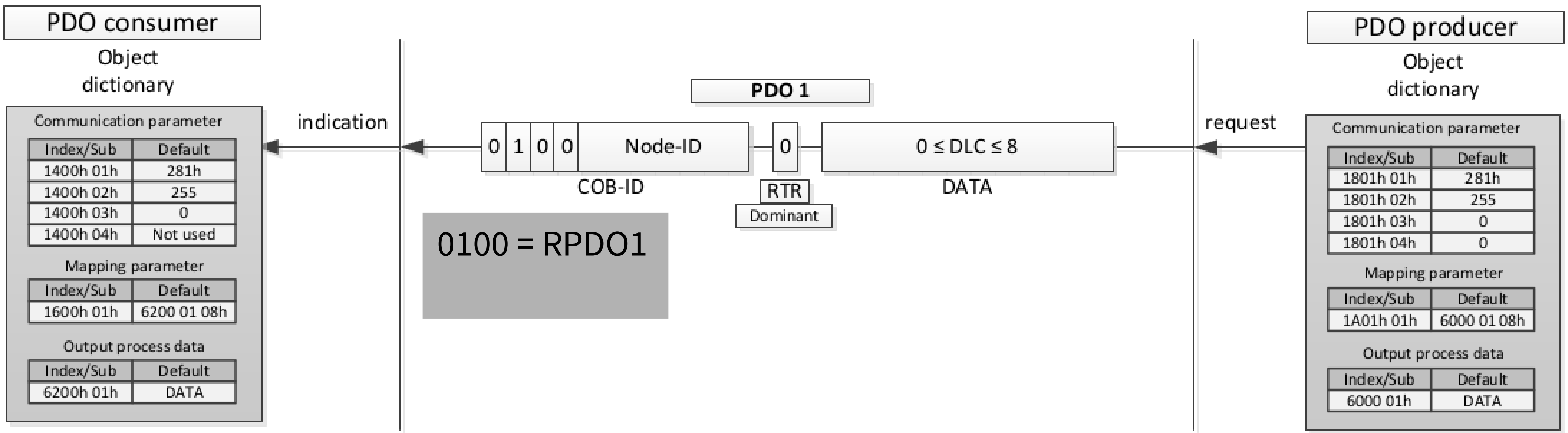


Figure 9-1: Unconfirmed Command exchange overview (example with PDO1)

Minimal implementation

9.4.3 Minimal set protocol data transmission

Data transmission exchange shall be triggered by either:

1. A Telemetry Request message
2. Or a SYNC message

When telemetry request data bytes are used…(they) shall contain the telemetry register(s) to be returned…

Minimal implementation

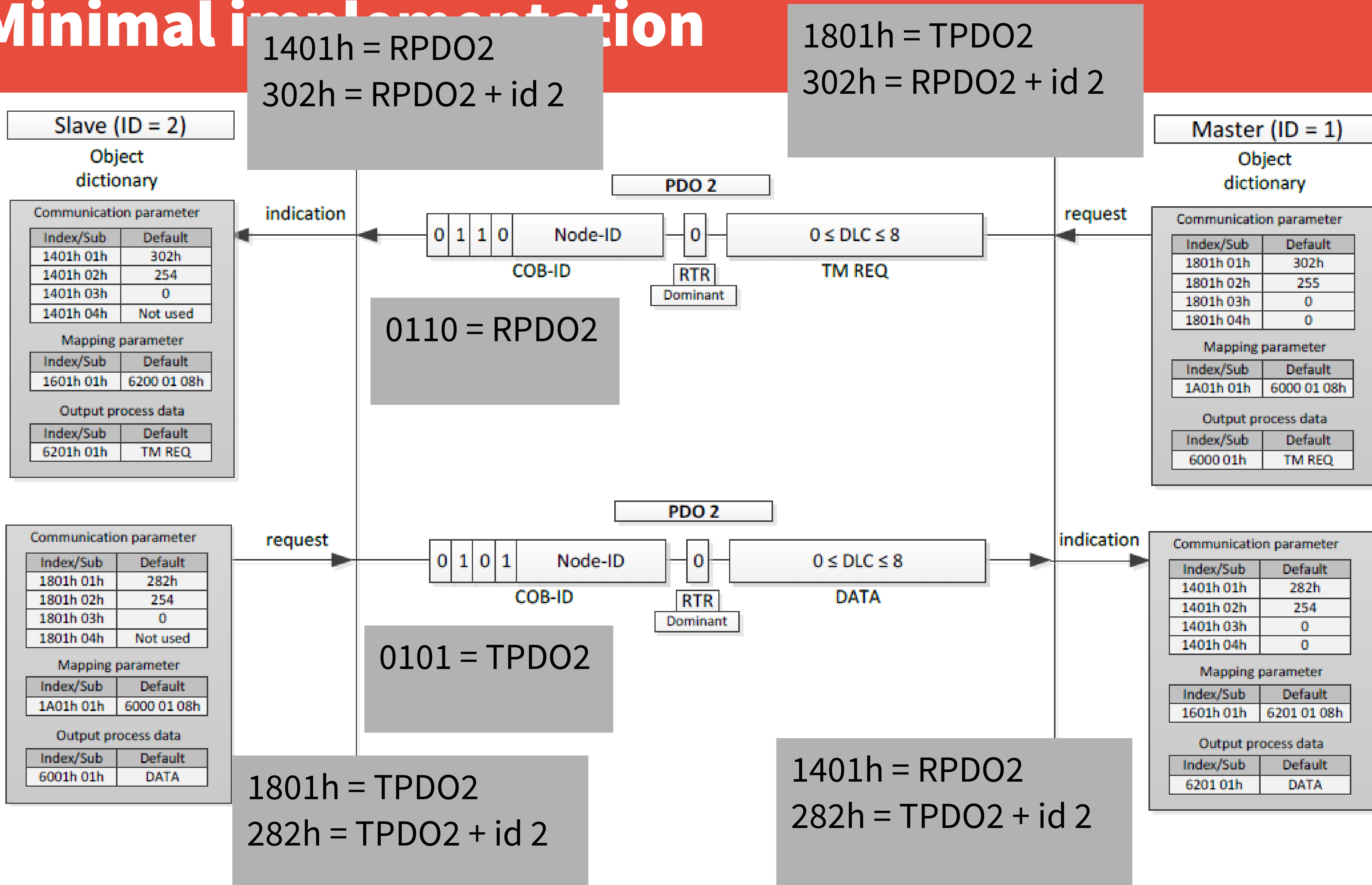


Figure 9-2: Telemetry request exchange overview (example with PDO2)

Prototype implementation – CANopen objects

	Slave			Master	
Object	**Function**	**COB-ID**		**Function**	**COB-ID**
TPDO1	Local SCET Get	TPDO1 + slave id		Spacecraft SCET Get	TPDO1 + master id
RPDO1	Local SCET Set	TPDO1 + master id			
TPDO2	-	-		Send TC	RPDO2 + slave id
RPDO2	Receive TC	RPDO2 + slave id		-	-
TPDO3	Send TM	TPDO3 + slave id		Send TM_REQ	RPDO3 + slave id
RPDO3	Receive TM_REQ	RPDO3 + slave id		Receive TM	TPDO3 + slave id
SYNC				Send SYNC	80h
HB	Send HB	700h + slave id		Send HB	700h + master id

Prototype implementation – PDO data field

PDO data field	
Function code	Data
2 Bytes	0 to 6 Bytes

65536 TCs requests + 6 bytes of data each
65536 TM REQUESTS

Prototype implementation - scenario

Master sends HB message every 250ms, fixed

Master sends SYNC every 5 sec, fixed

Master loops:

- sends SCET PDO every ~10 sec
- sends dummy TC every ~0.1 sec
- sends dummy TM REQ every ~0.1 sec

Slave toggles LED on HB

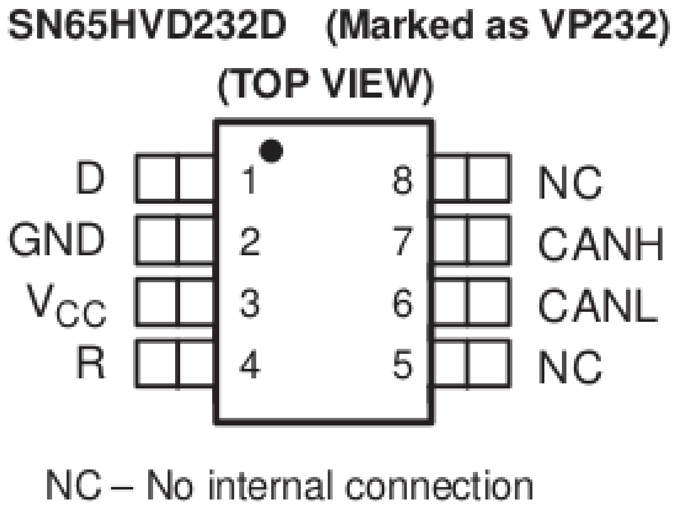
Slave toggles LED on SYNC

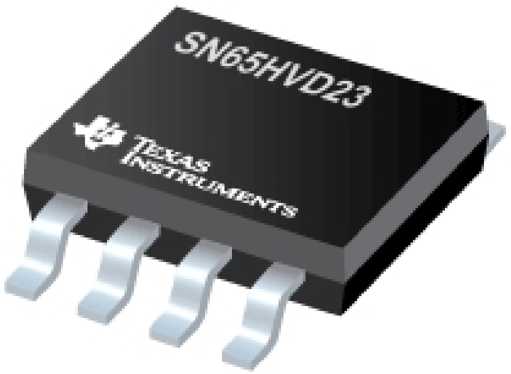
Slave toggles LED on SCET

Slave responds to TM REQ with dummy TM

Prototype implementation - transceiver

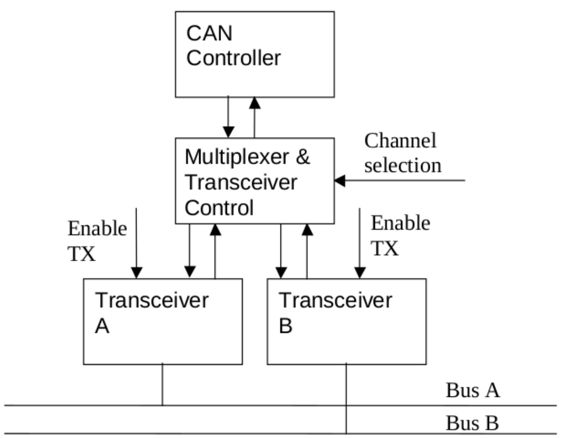
- Texas Instruments SN65HVD23x 3.3-V CAN Bus Transceivers
- Fully ISO11898-2 compliant, supports 1 Mbps
- 3.3V power supply
- In high-impedance when unpowered

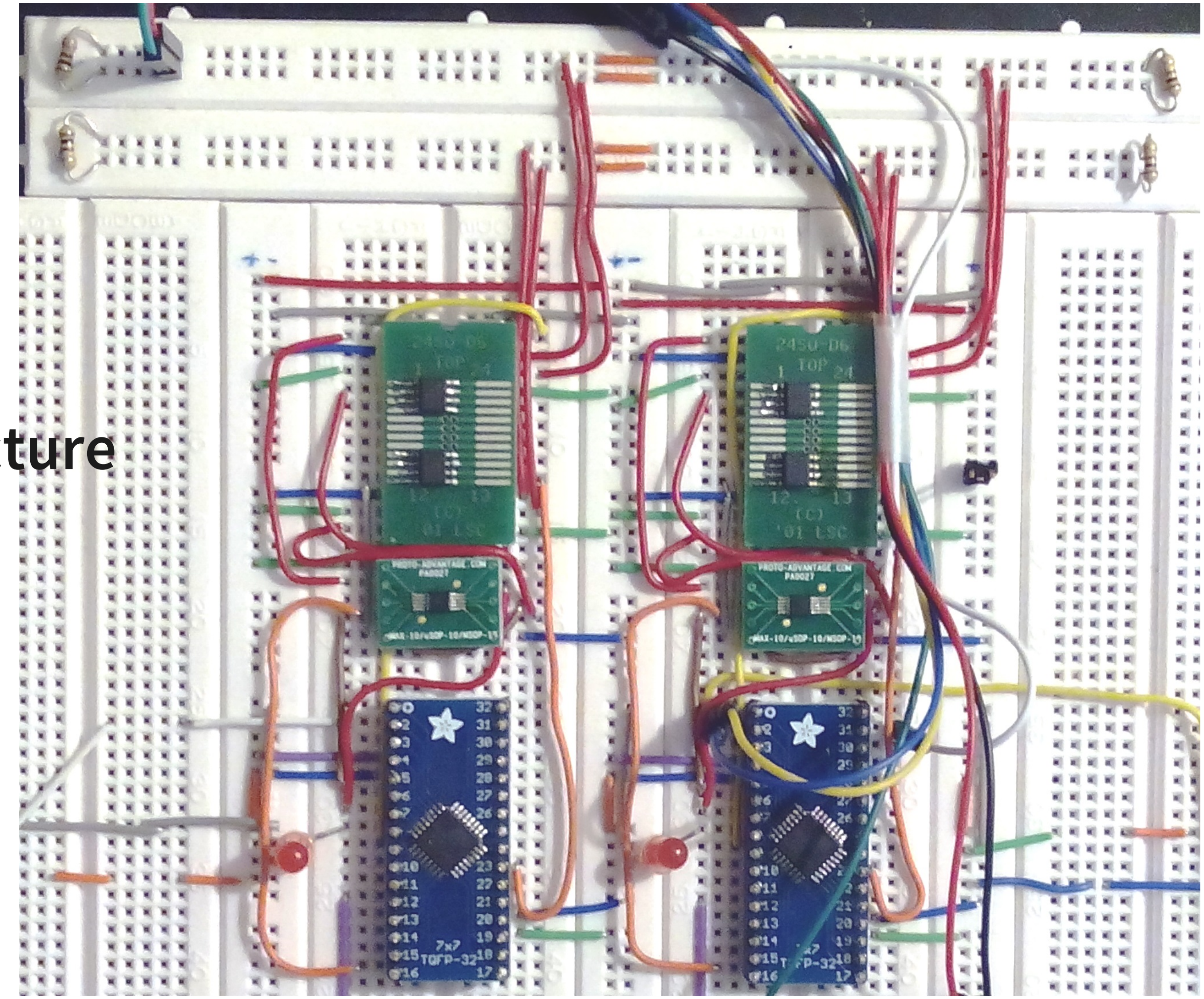




Prototype 1 - overview

- 8-bit Atmel AVR
- Atmega16m1
- C language
- Selective bus architecture





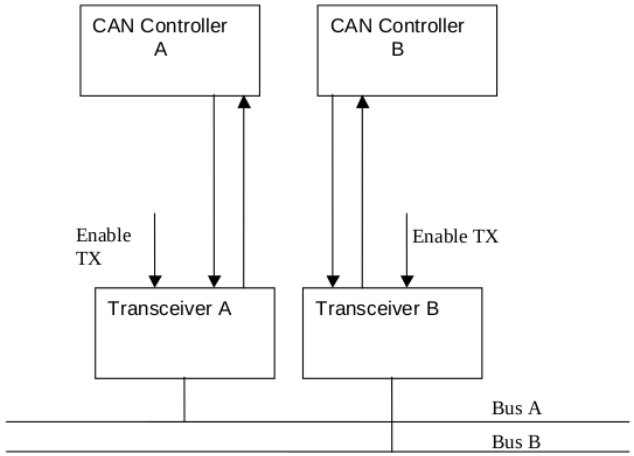
Prototype 1 – code snippets

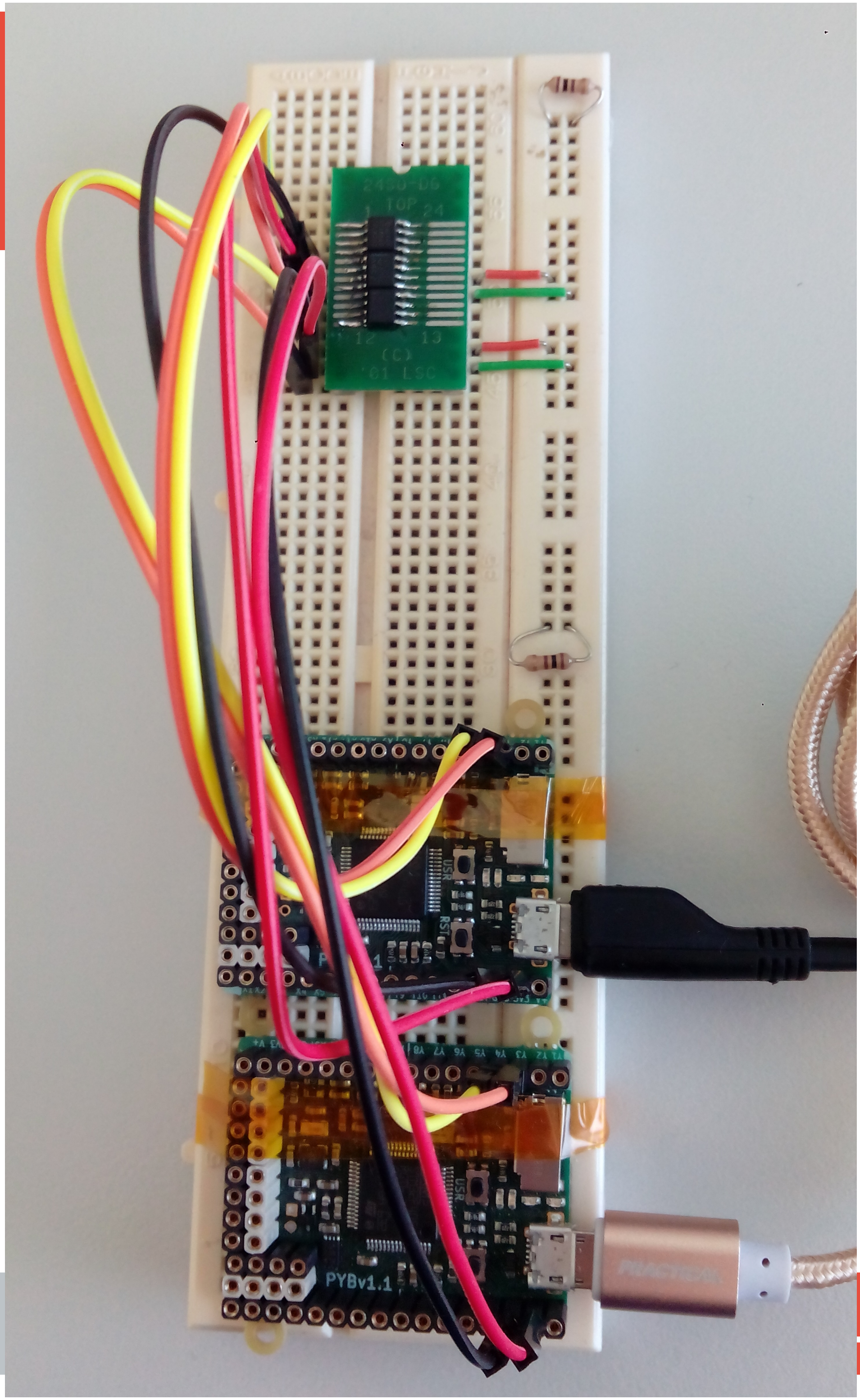
```
int8_t canopen_send_tpdo(const uint16_t tpdo_index)
{
    struct can_frame_t can_frame;
    uint16_t tpdo_map;
    uint32_t map;
    uint16_t index;
    uint8_t subindex;
    uint16_t i;
    uint16_t j;

    /* Check that pdo_index is within valid range for TPDO*/
    assert ((tpdo_index >= CANOPEN_TPDO_INDEX)
            && (tpdo_index < CANOPEN_TPDO_MAP_INDEX));
    /* Check that current canopen state allows sending of tpdo */
    if (canopen_get_state() != canopen_state_OPERATIONAL)
    {
        return -1;
    }

    i = canopen_find_index(tpdo_index);
    /* Set COB-ID */
    can_frame.id = ((struct canopen_pdo_t*)canopen_od[i].object)->cob_id;
    /* Set DLC */
    tpdo_map = canopen_find_index(tpdo_index + 0x200);
    can_frame.dlc = ((struct canopen_pdo_map_t *)
                        canopen_od[tpdo_map].object)->number_of_entries;

    for (i = 0; i < can_frame.dlc; i++)
    {
        map = ((struct canopen_pdo_map_t *)canopen_od[tpdo_map].object)->map[i];
        index = (map >> 16);
        subindex = (map >> 8) & 0xFF;

        j = canopen_find_index(index);
        can_frame.data[i] = ((struct canopen_pdb_t *)
                                canopen_od[j].object)->var[subindex];
    }

    can_send(CAN_MOB_TX, &can_frame);
    return 0;
}
```

```
void can_configure_receive(const uint8_t mob,
                           const struct can_frame_t* can_frame)
{
    uint8_t page_saved;

    assert (mob < CAN_MOB_MAX);
    /* Enable reception of CAN frames from the network master */
    page_saved = CANPAGE;
    CANPAGE = mob << MOBNB0; /* use MOb for Rx and auto-increment data index */
    CANSTMOB = 0x00; /* clear all MOb status flags */
    CANIDM4 = (1 << RTRMSK) | (1 << IDEMSK); /* set mask for rtr and ide */
    CANIDM3 = 0x00;
    CANIDM2 = (can_frame->id_mask & 0x07) << 5;
    CANIDM1 = can_frame->id_mask >> 3;
    CANIDT4 = 0x00; /* clear rtr and ide bits */
    CANIDT3 = 0x00;
    CANIDT2 = (can_frame->id & 0x07) << 5;
    CANIDT1 = can_frame->id >> 3;
    CANCDMOB = (1 << CONMOB1) | (can_frame->dlc << DLC0); /* enable reception */
    CANPAGE = page_saved;
    CANIE1 = 0; /* compatibility with future chips */
    CANIE2 |= (1 << mob); /* Enable receive MOb interrupts */
    CANGIE = (1 << ENIT) | (1 << ENRX); /* Enable interrupts: global, receive */
}
```

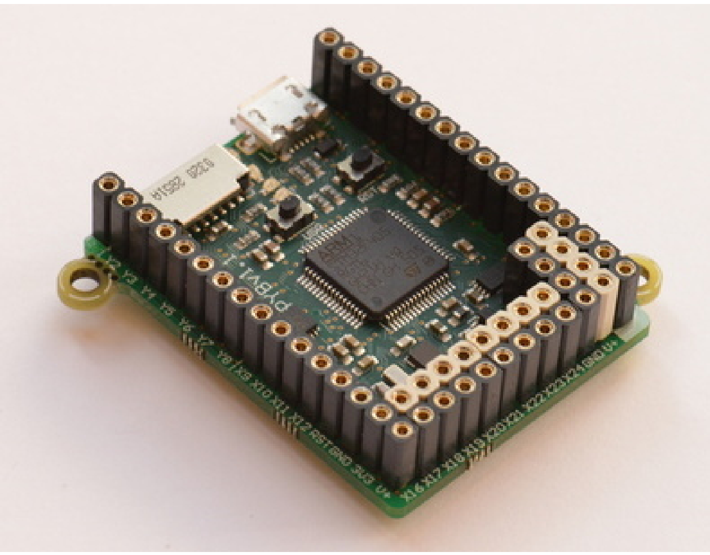
Prototype 2 - overview

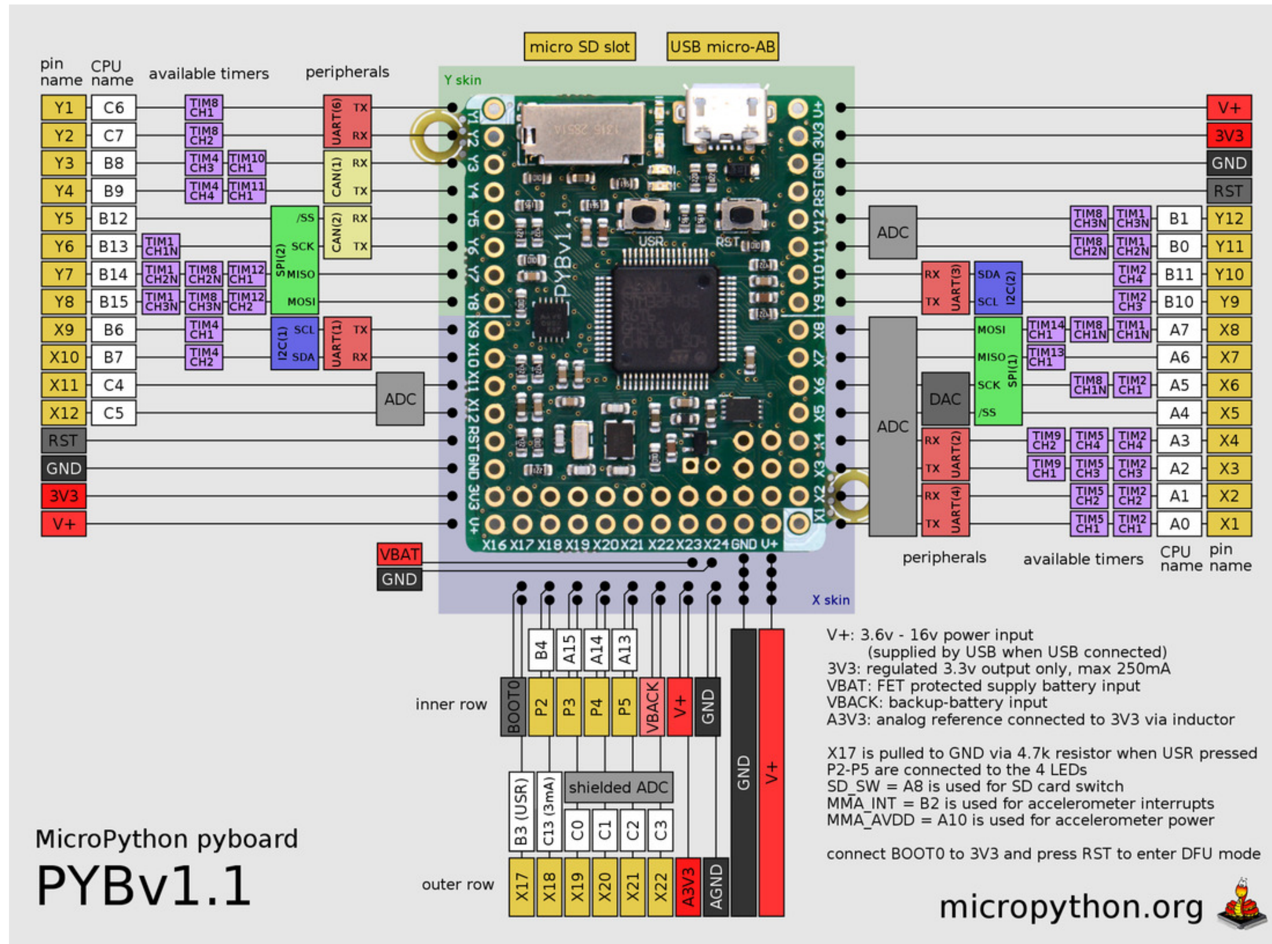
- 32-bit ARM
- STM32F405RGT6
- Micropython language
- Parallel bus architecture





Prototype 2 – pyboard






```
from pyb import LED
from pyb import delay

led = LED(1)

while True:
    led.toggle()
    delay(1000)
```

Prototype 2 – code snippets

```python
from .frame import DataFrame


class Pdo:
    def __init__(self, node,
                 tpdo_index, tpdo_map_index, rpdo_index, rpdo_map_index):
        self.node = node
        self.tpdo_index = tpdo_index
        self.tpdo_map_index = tpdo_map_index
        self.rpdo_index = rpdo_index
        self.rpdo_map_index = rpdo_map_index

    def transmit(self, node_id):
        """Send a TPDO."""
        cob_id = self.node.od[self.tpdo_index][1].value + node_id
        map_record = self.node.od[self.tpdo_map_index]
        no_of_mappings = map_record[0].value

        data = []
        # go through all mapping entries
        for i in range(1, no_of_mappings + 1):
            s = map_record[i].value  # mapping is recorded as string
            od_index = int(s[0:4], 16)  # extract od index from hex string
            od_subindex = int(s[4:6], 16)
            length = int(s[6:8], 16)
            octets = int(length / 8)
            # read the value as stored in the od at given location
            val = self.node.od[od_index][od_subindex].value
            # append the value bytewise to data list
            for octet in range(octets):
                # append data with LSB first
                data.append((val >> octet * 8) & 0xff)

        self.frame = DataFrame(frame_id=cob_id, data=data)
        self.node.network.send_frame(self.frame)
```

Prototype 2 – code snippets

```python
import time
import pyb
import micropython
from canopen import Bus, Network, Node, NmtSlave
import slave_eds
micropython.alloc_emergency_exception_buf(100)


# define main and redundant bus
bus_a = Bus(1, mode=pyb.CAN.NORMAL)
bus_b = Bus(2, mode=pyb.CAN.NORMAL)

# create network
network = Network()
network.connect(bus_a, bus_b)
network.set_active_bus(bus_a)

# create slave node from object dictionary
slave_node = Node(slave_eds.od)
network.add_node(slave_node)

# create NMT slave and start HB reception
nmt_slave = NmtSlave(slave_node)
nmt_slave.heartbeat.start()

# create SYNC object and associate process function
nmt_slave.sync.start()

def sync_function():
    print("info: sync received")

nmt_slave.sync.callback = sync_function

# define message reception filter
FIFO_0 = 0
FILTERBANK_0 = 0
FILTERBANK_1 = 1
network.active_bus.can.setfilter(
    FILTERBANK_0, pyb.CAN.LIST16, FIFO_0, (0x080, 0x701, 0x181, 0x000))
network.active_bus.can.setfilter(
    FILTERBANK_1, pyb.CAN.LIST16, FIFO_0, (0x282, 0x382, 0x000, 0x000))
```

```python
try:
    while True:
        if network.active_bus.can.any(FIFO_0):
            message_id, _, _, can_data = network.active_bus.can.recv(0)

            if message_id == 0x701:
                nmt_slave.heartbeat.received()
            elif message_id == 0x080:
                nmt_slave.sync.received()
            elif message_id == 0x181:
                SCET = int.from_bytes(can_data[3:8], 'little')
                SCET_ms = int.from_bytes(can_data[0:3], 'little')
                print("info: received SCET {} sec + {}/256 sec".format(
                    SCET, SCET_ms))
            elif message_id == 0x282:
                # react upon TC
                # ...
                # statistics
                tc_received += 1
                if tc_received % 100 == 0:
                    tc_code = int.from_bytes(can_data[0:2], 'little')
                    tc_data = int.from_bytes(can_data[2:8], 'little')
                    print("info: received 100 TCs, last with code {} and data {}".format(
                        tc_code, tc_data))
            elif message_id == 0x382:
                tm_req_code = int.from_bytes(can_data[0:2], 'little')
                # send out TM reply
                slave_eds.tm_request.value = tm_req_code
                slave_eds.tm_data.value = 0x665544332211
                print("info: send TM reply")
                slave_node.pdo[3].transmit(slave_node.id + 1)
                # statistics
                tm_req_received += 1
                if tm_req_received % 500 == 0:
                    print("info: received and replied 500 TM_REQs, last with code {}".format(
                        tm_req_code))

except KeyboardInterrupt:
    nmt_slave.heartbeat.stop()
    nmt_slave.sync.stop()
    network.active_bus.can.rxcallback(0, None)
```

Prototype 2 – code snippets

```
# create objectdictionary
od = canopen.ObjectDictionary()

# define node id
od.node_id = 2

# define standard entries
od.add_object(0x1006, canopen.Variable(5000000, "Communic. cycle period (usec)"))
od.add_object(0x1016, canopen.Variable(2500, "Consumer heartbeat time (msec)"))

# Redundancy Management
rec = canopen.Record("Redundancy management")
rec.add_member(1, canopen.Variable(1, "Bdefault"))
rec.add_member(2, canopen.Variable(5, "Ttoggle"))
rec.add_member(3, canopen.Variable(10, "Ntoggle"))
rec.add_member(4, canopen.Variable(0, "Ctoggle"))
od.add_object(0x2000, rec)

# RPDO3 for TM_REQUEST reply
rec = canopen.Record("RPDO3 parameter")
rec.add_member(0, canopen.Variable(2))
rec.add_member(1, canopen.Variable(canopen.COB_ID_RPDO_3))
rec.add_member(2, canopen.Variable(254, "transmission type"))
od.add_object(0x1802, rec)
rec = canopen.Record("RPDO3 mapping")
rec.add_member(0, canopen.Variable(2))
rec.add_member(1, canopen.Variable("61000110", "TM request mapping"))
rec.add_member(2, canopen.Variable("61000230", "TM data mapping"))
od.add_object(0x1A02, rec)
tm_request = canopen.Variable(0x0001)
tm_data = canopen.Variable(0x000000000000)
rec = canopen.Record("Reply TM_REQUEST")
rec.add_member(0, canopen.Variable(2))
rec.add_member(1, tm_request)
rec.add_member(2, tm_data)
od.add_object(0x6100, rec)
```

Conclusion

- Both implementation work satisfactorily
- Needs to be tested with several slave nodes and data processing

- All code is made available open source and free of charge
- Python is great for prototyping
- Embedded C is needed for constraint environments

- ECSS minimal implementation needs further clarification, e.g. Master Redundancy Management, PDO exchange

- librecube.net → Contribute → Work Packages → code repository
- Feedback in the forum, mailing list, or in repository