A Model-based Certification Framework for the EnergyBus Standard

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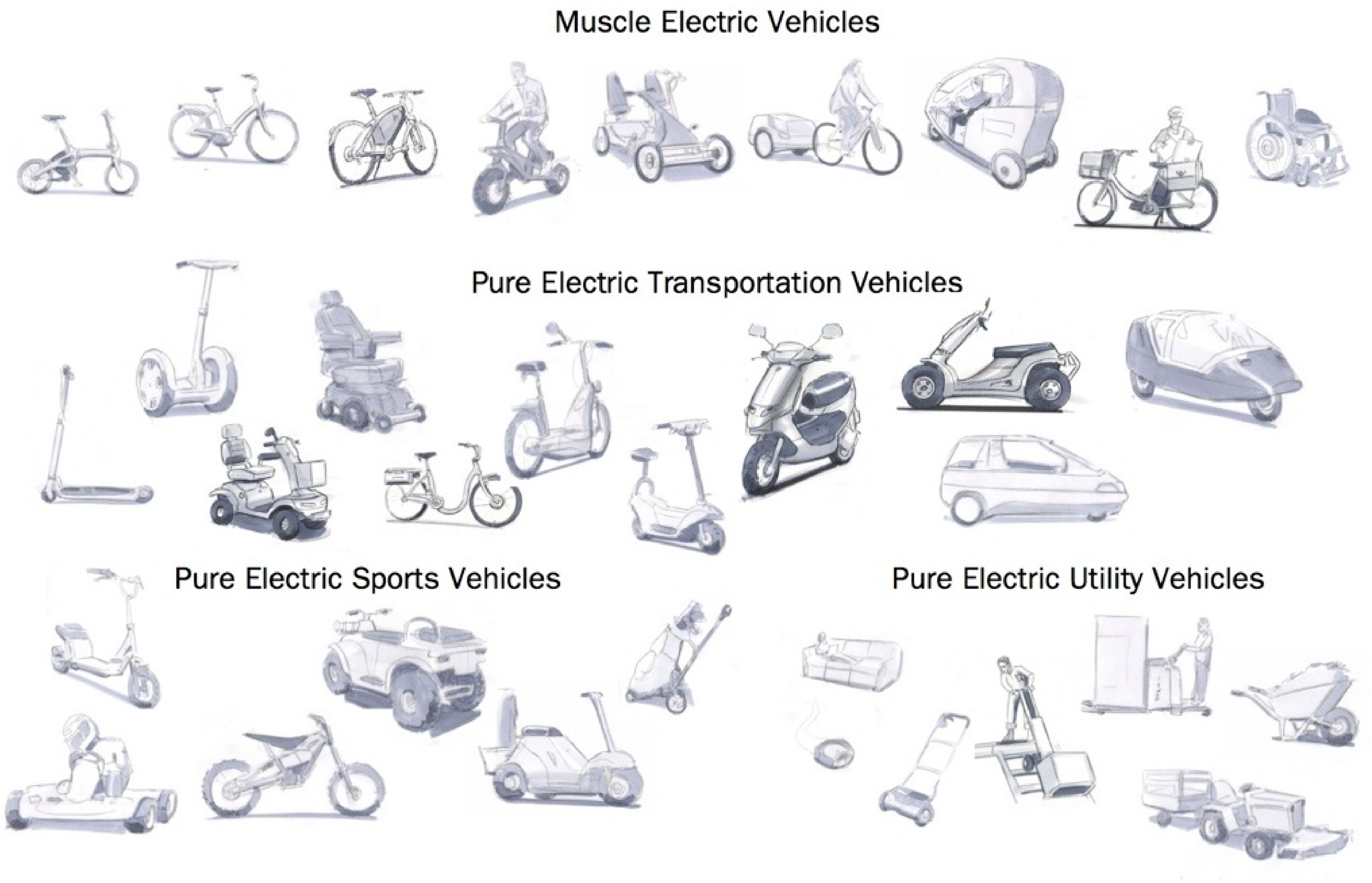
Light Electric Vehicles

LEV Product Groups and Markets


Muscle Electric Vehicles
Pure Electric Transportation Vehicles
Pure Electric Sports Vehicles
Pure Electric Utility Vehicles

Light Electric Vehicles

- rapidly growing market
- big OEMs and suppliers

BOSCH

Panasonic

- fleet administrators

DB

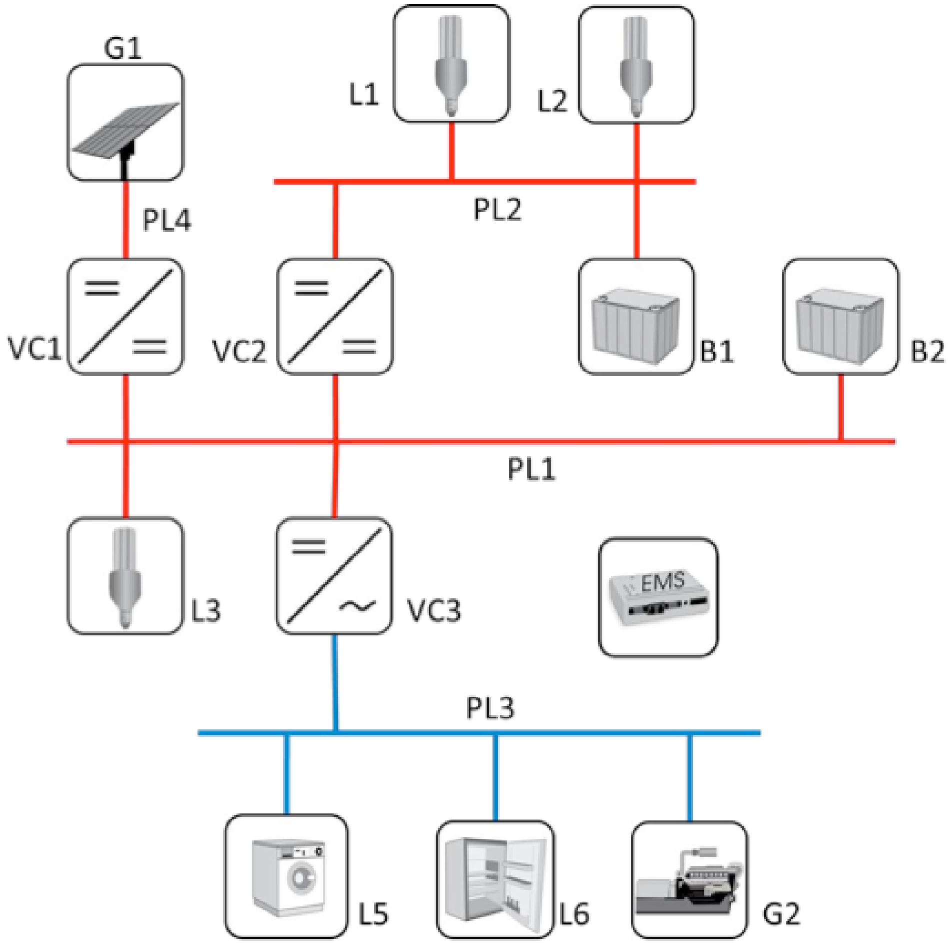
- bike vendors entering this market

Light Electric Vehicles

- need for Energy Management Systems
- proprietary solutions
  - incompatible connectors and platforms
  - no exchange of components

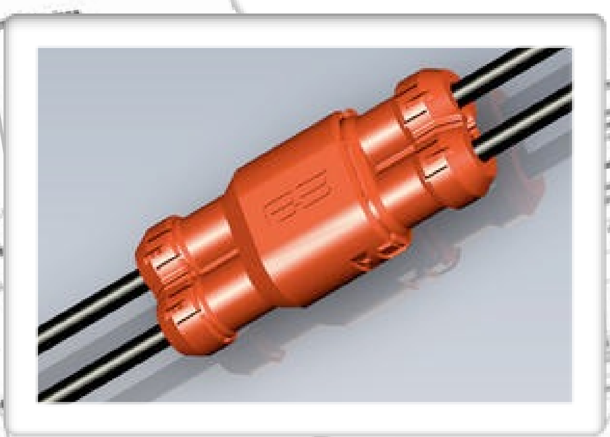
- safety critical application
  - distribution of electrical power
  - battery explosion

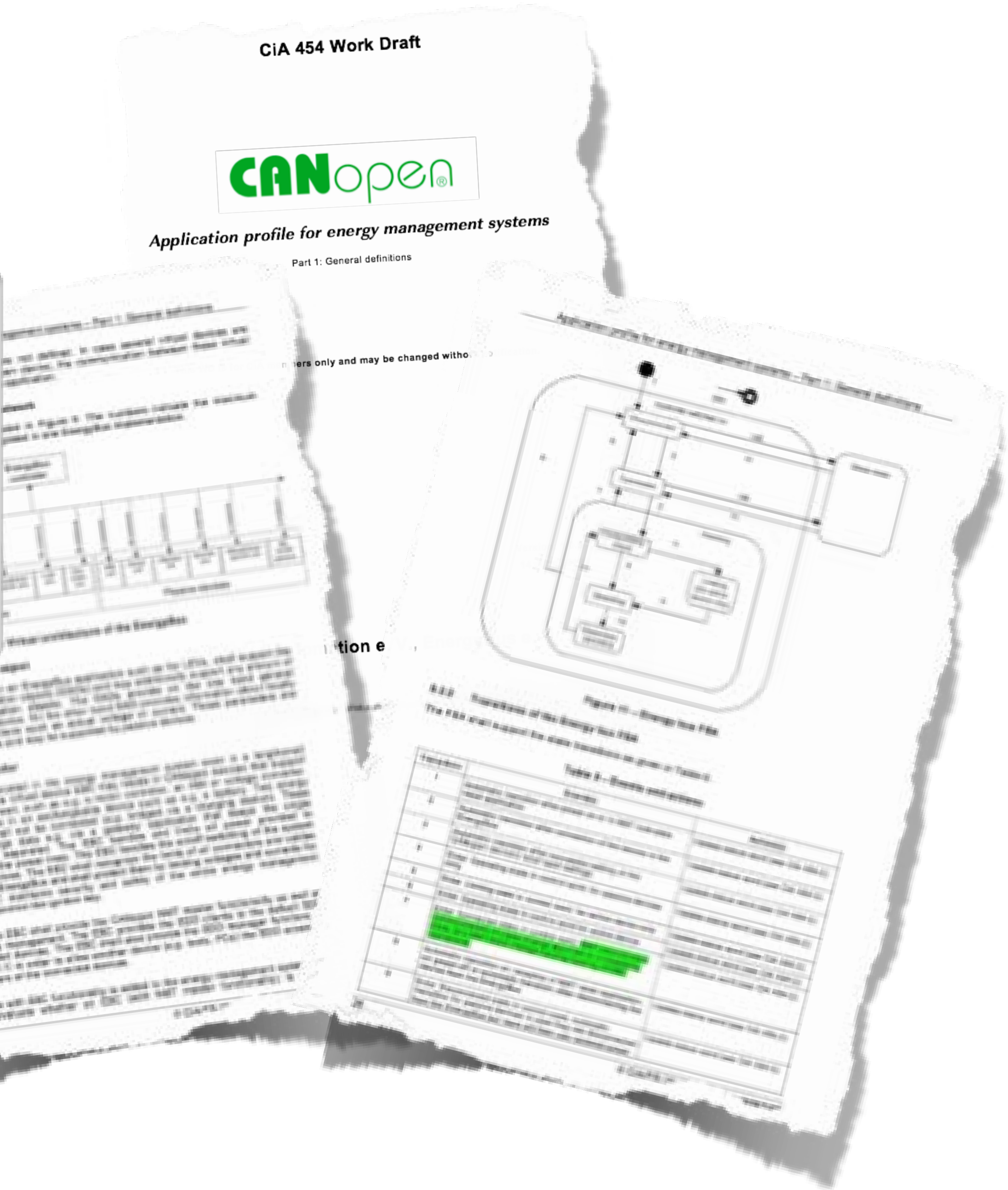
Stationary Applications



EnergyBus e.V.

- a universal standard for Energy Management Systems
- implementation of official certification procedure





CiA 454 Work Draft

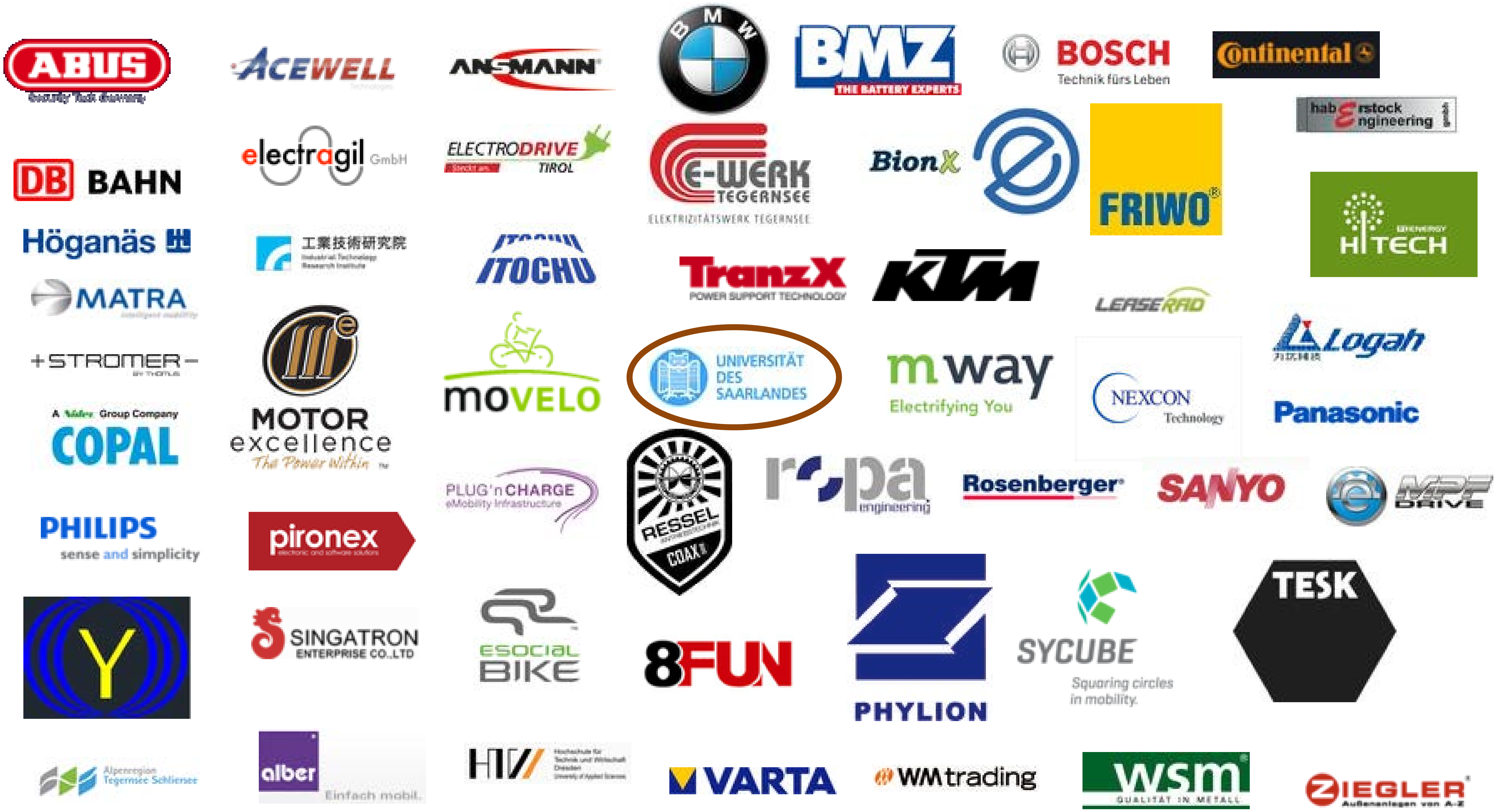
CANopen

Application profile for energy management systems

Part 1: General definitions

EnergyBus e.V.

EnergyBus



Outline

- EnergyBus documentation
  - overview of CAN / CANopen
  - EnergyBus extension

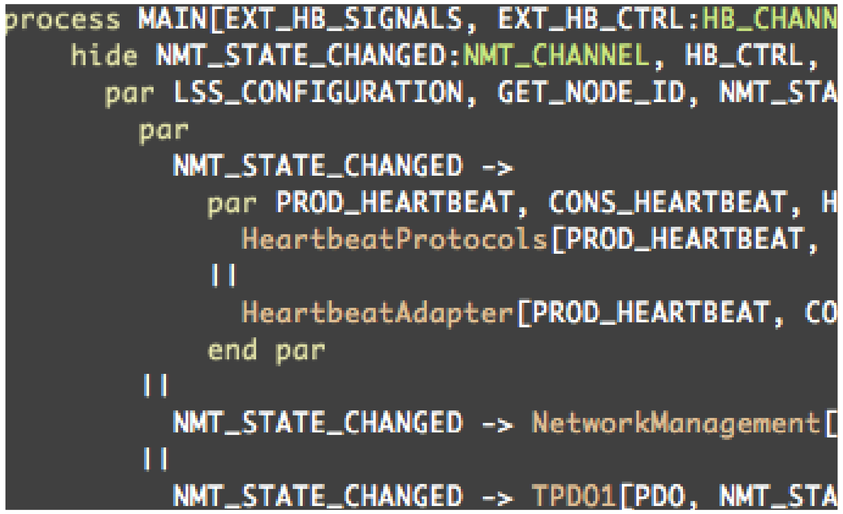
CiA 454 Work Draft

CANopen

Application profile for energy management systems

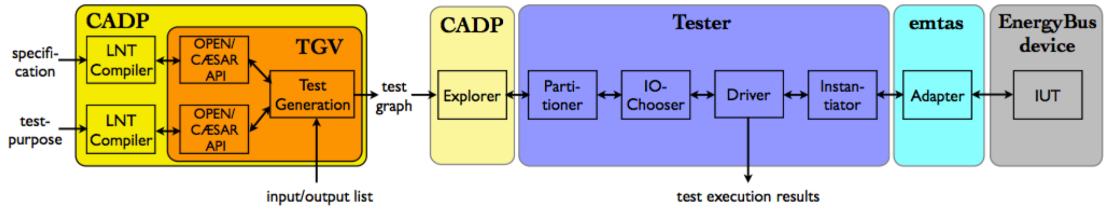
Part 1: General definitions

- Formal specification
  - modeling techniques
  - specification issues



```
process MAIN[EXT_HB_SIGNALS, EXT_HB_CTRL:HB_CHANN
    hide NMT_STATE_CHANGED:NMT_CHANNEL, HB_CTRL,
      par LSS_CONFIGURATION, GET_NODE_ID, NMT_STA
        par
          NMT_STATE_CHANGED ->
            par PROD_HEARTBEAT, CONS_HEARTBEAT, H
              HeartbeatProtocols[PROD_HEARTBEAT,
            ||
              HeartbeatAdapter[PROD_HEARTBEAT, CO
            end par
        ||
          NMT_STATE_CHANGED -> NetworkManagement[
        ||
          NMT_STATE_CHANGED -> TPDO1[PDO, NMT_STA
```

- Certification framework
  - Model-based testing
  - tool setup
  - abstraction techniques
  - testing results



EnergyBus Documentation

CiA 454 Work Draft

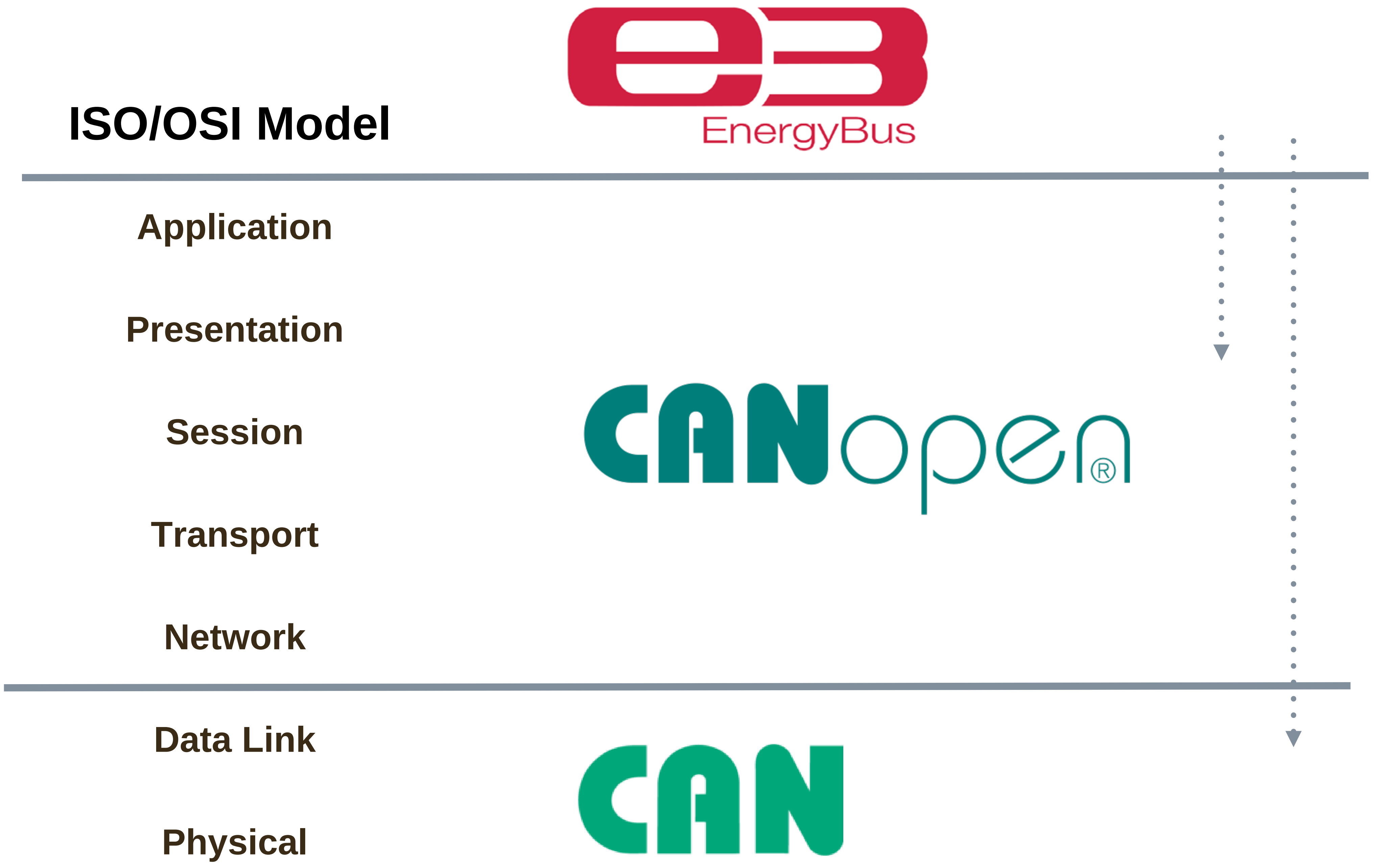
CANopen

Application profile for energy management systems

Part 1: General definitions

bers only and may be changed without

Protocol Stack



ISO/OSI Model

Application

Presentation

Session

Transport

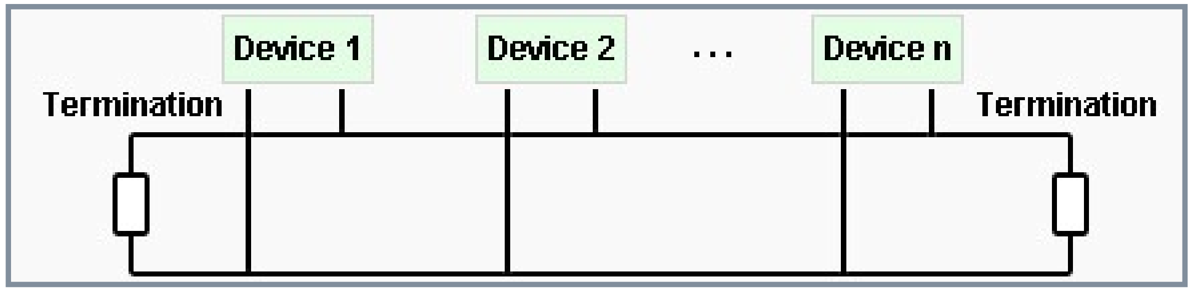
Network

Data Link

Physical

CAN / CANopen

- Bus arbitration: CSMA/BA
- Network topology



- CAN/CANopen frame

function code	node ID	RTR	data length	Data
4 bits	7 bits	1 bit	4 bits	0-8 bytes

CANopen

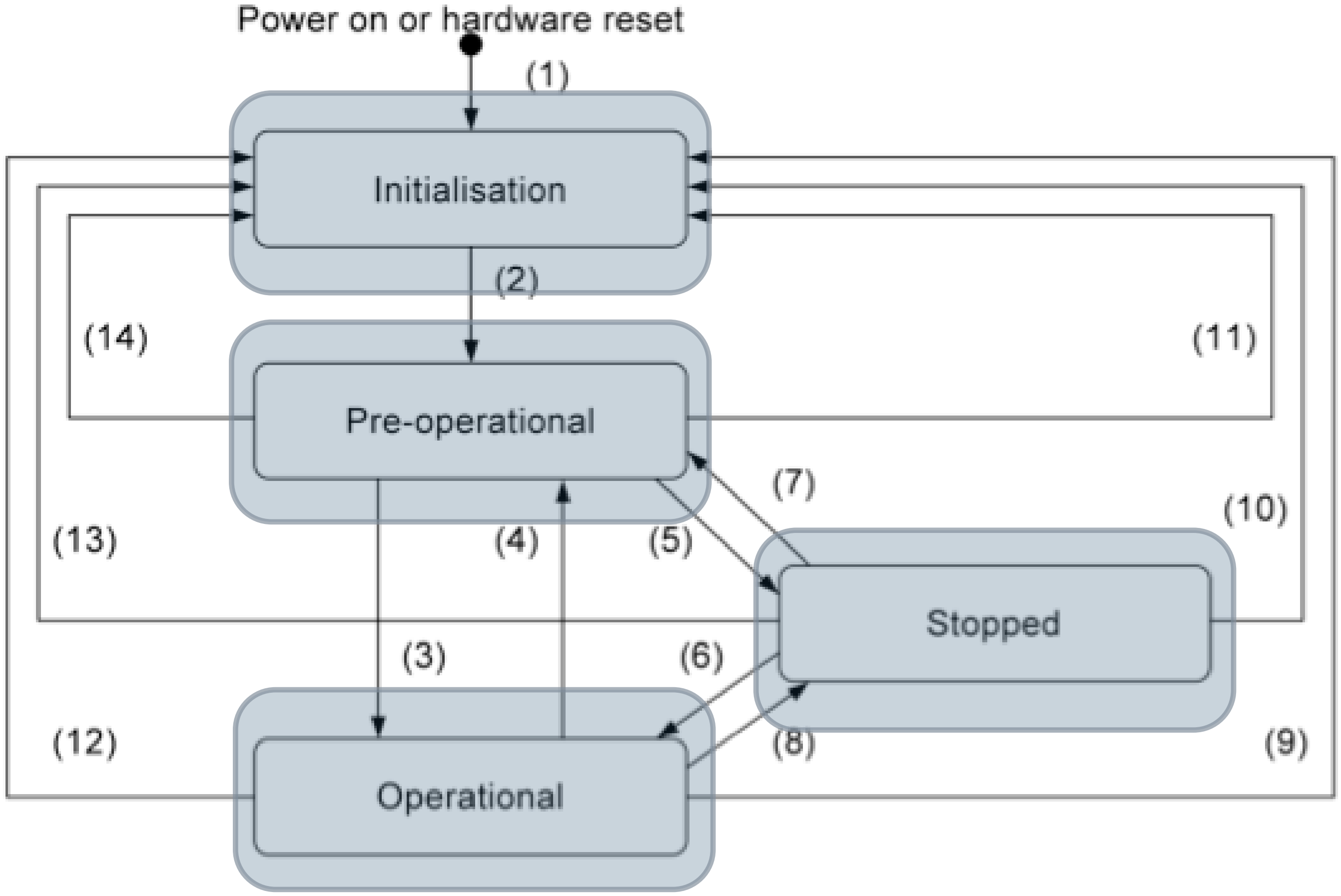
- defines various services
  - NMT
  - SDO
  - PDO
  - LSS
  - Node control
  - SYNC
  - EMCY
  - TIME

CANopen Services

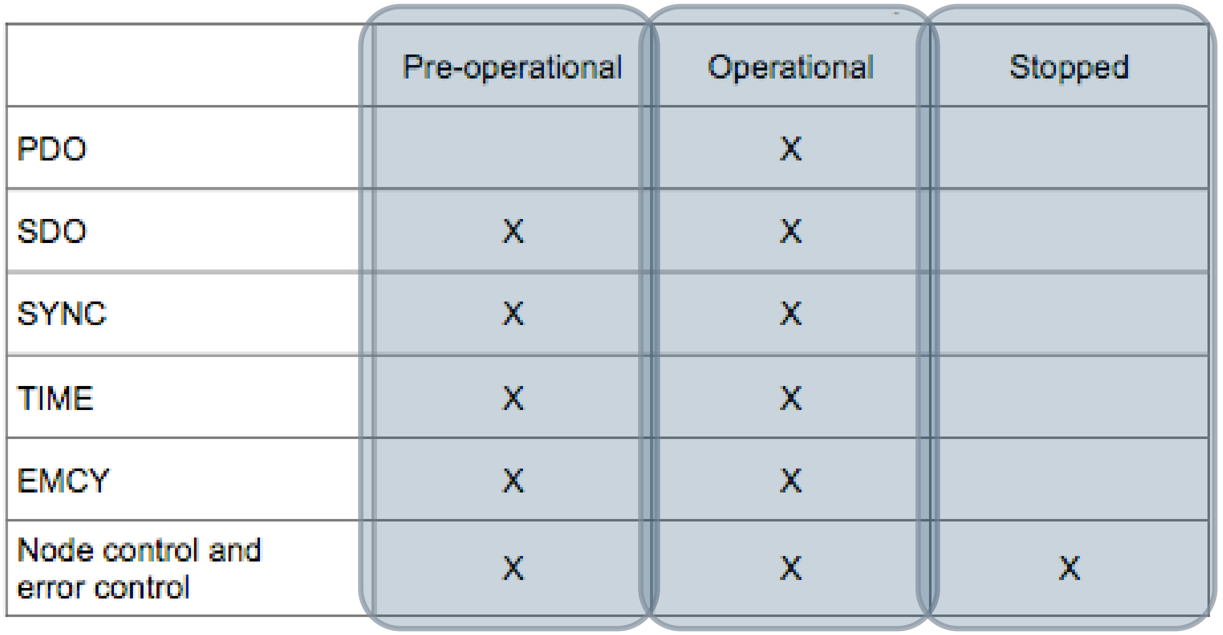
Network Management (NMT)

- master/slave protocol
- operational state

NMT Automaton



Communication capability



	Pre-operational	Operational	Stopped
PDO		X	
SDO	X	X	
SYNC	X	X	
TIME	X	X	
EMCY	X	X	
Node control and error control	X	X	X

CANopen Services

Service Data Object (SDO) communication:

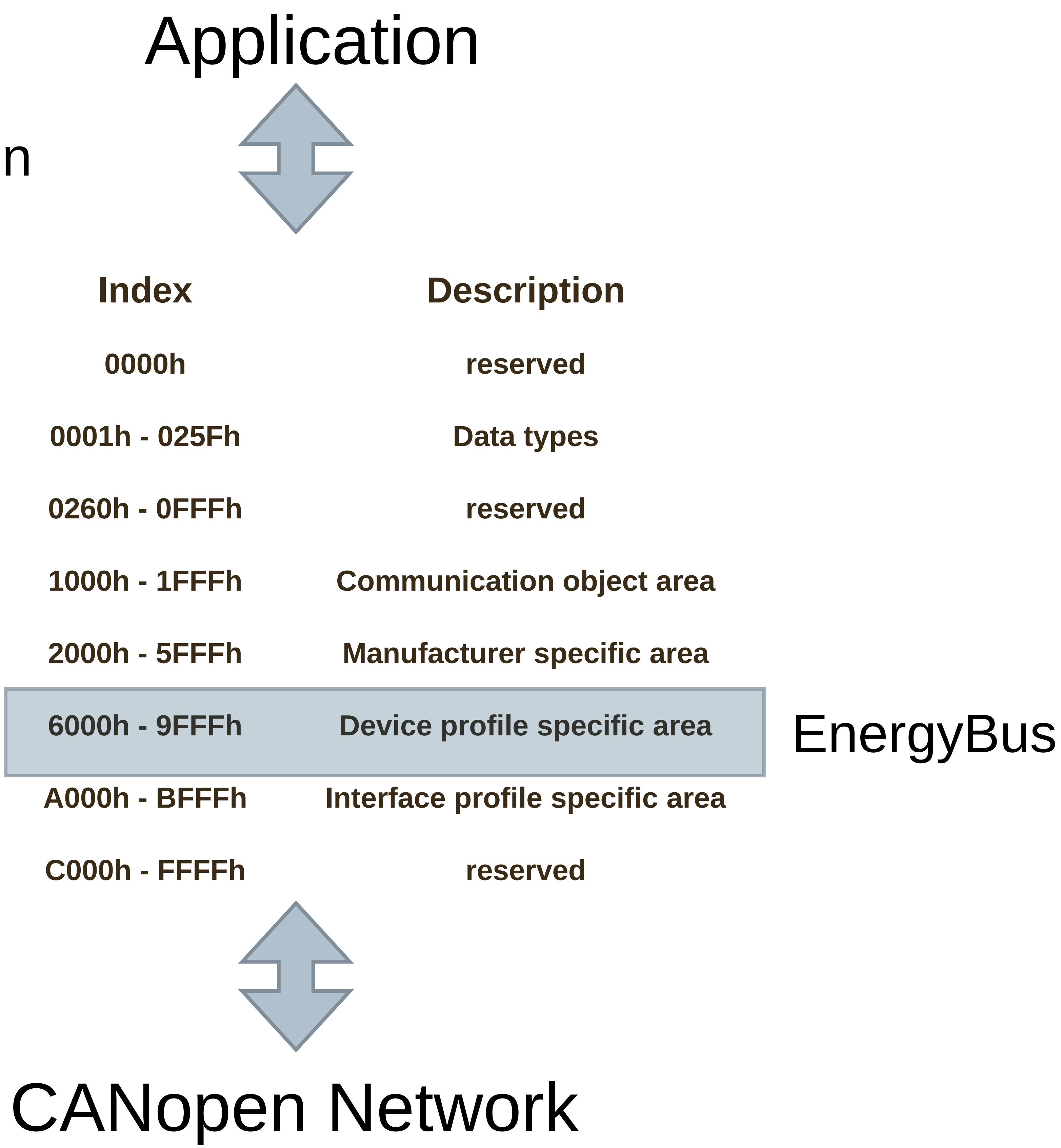
- binary communication
- server/client protocol
- configuration
- segmentation, acknowledgements

Process Data Object (PDO) communication:

- broadcast communication
- producer/consumer protocol
- dynamic data exchange, notifications
- single frame (max. 8 data bytes)

Object Directory (OD)

- 16-bit main index
- 8-bit sub-index
- service configuration
- data exchange



Application

Index	Description
0000h	reserved
0001h - 025Fh	Data types
0260h - 0FFFh	reserved
1000h - 1FFFh	Communication object area
2000h - 5FFFh	Manufacturer specific area
6000h - 9FFFh	Device profile specific area
A000h - BFFFh	Interface profile specific area
C000h - FFFFh	reserved

EnergyBus

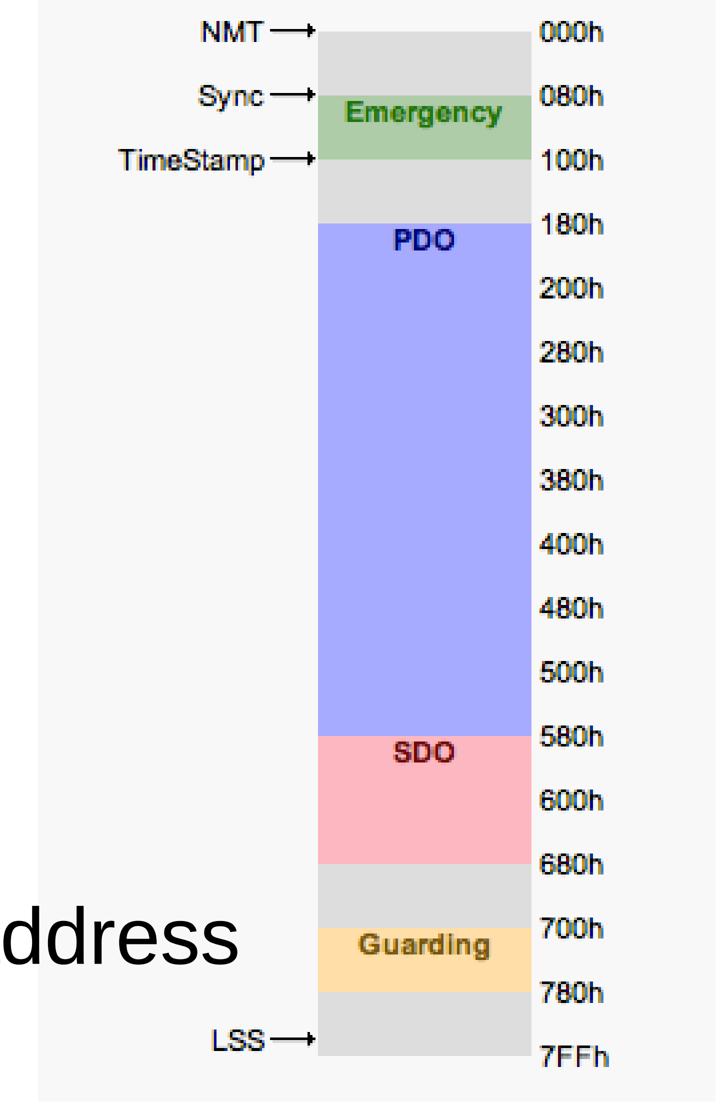
CANopen Network

CANopen Services

Layer Setting Service (LSS):

- master/slave protocol
- independent of NMT state
- detection of connected/unconfigured devices
- configuration of node-ID
- identification by device-specific 8-byte LSS address

highest priority

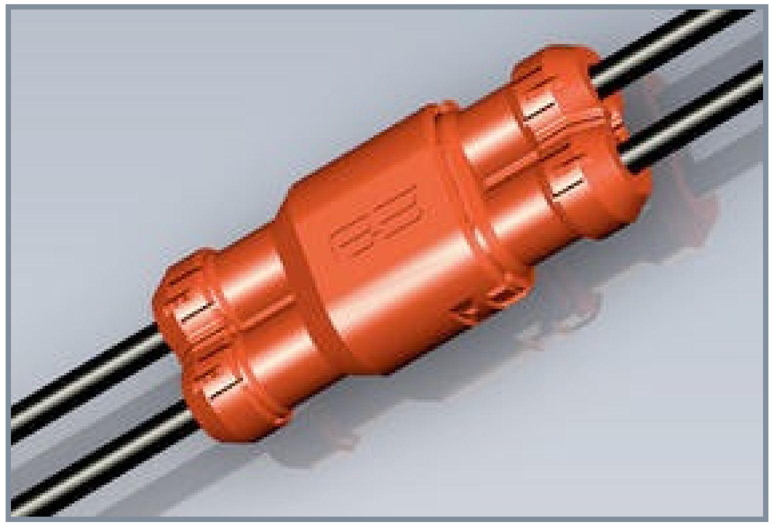


lowest priority

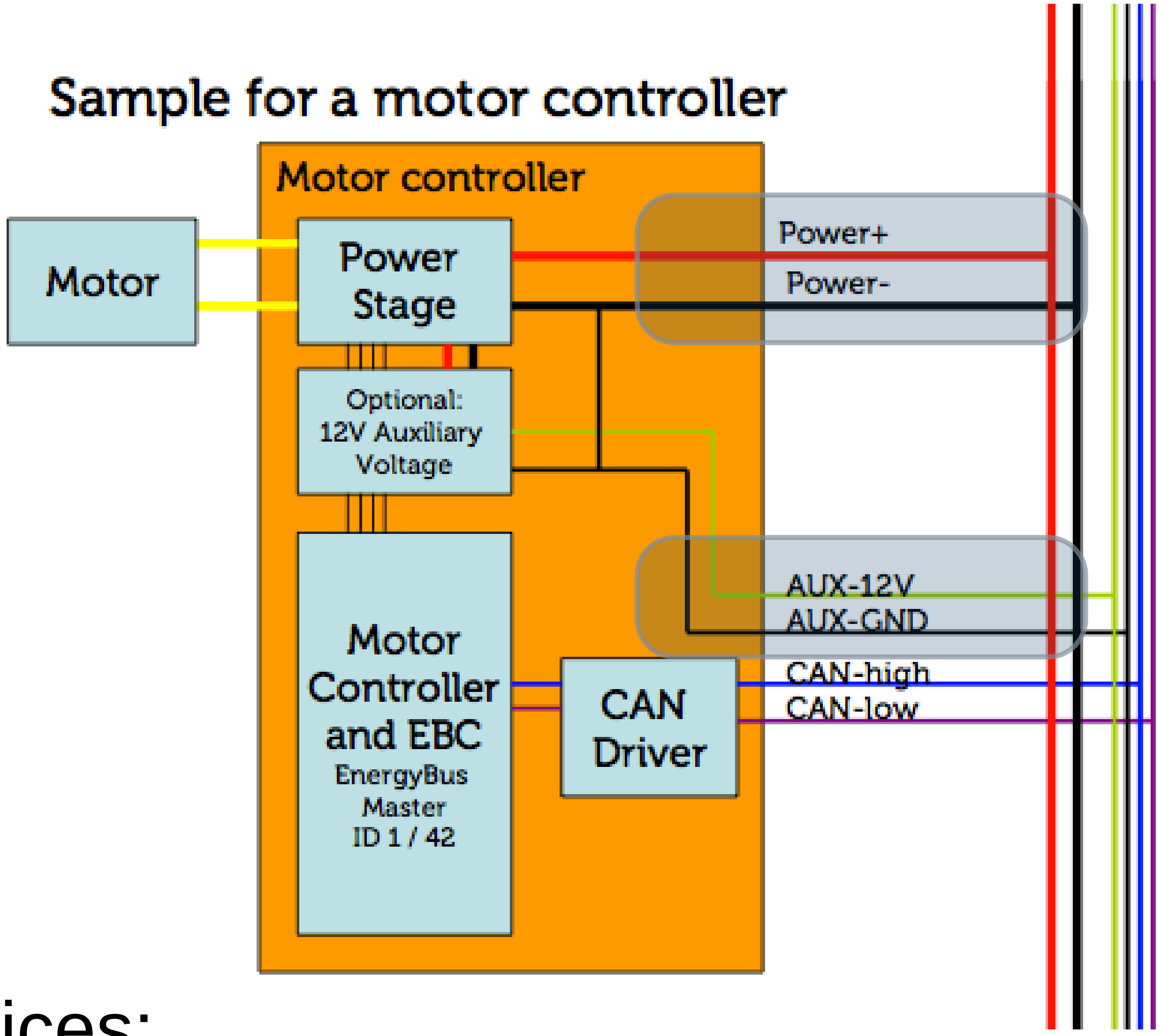
EnergyBus

Hardware aspects

- family of connectors
- additional power lines (MAIN and AUX)



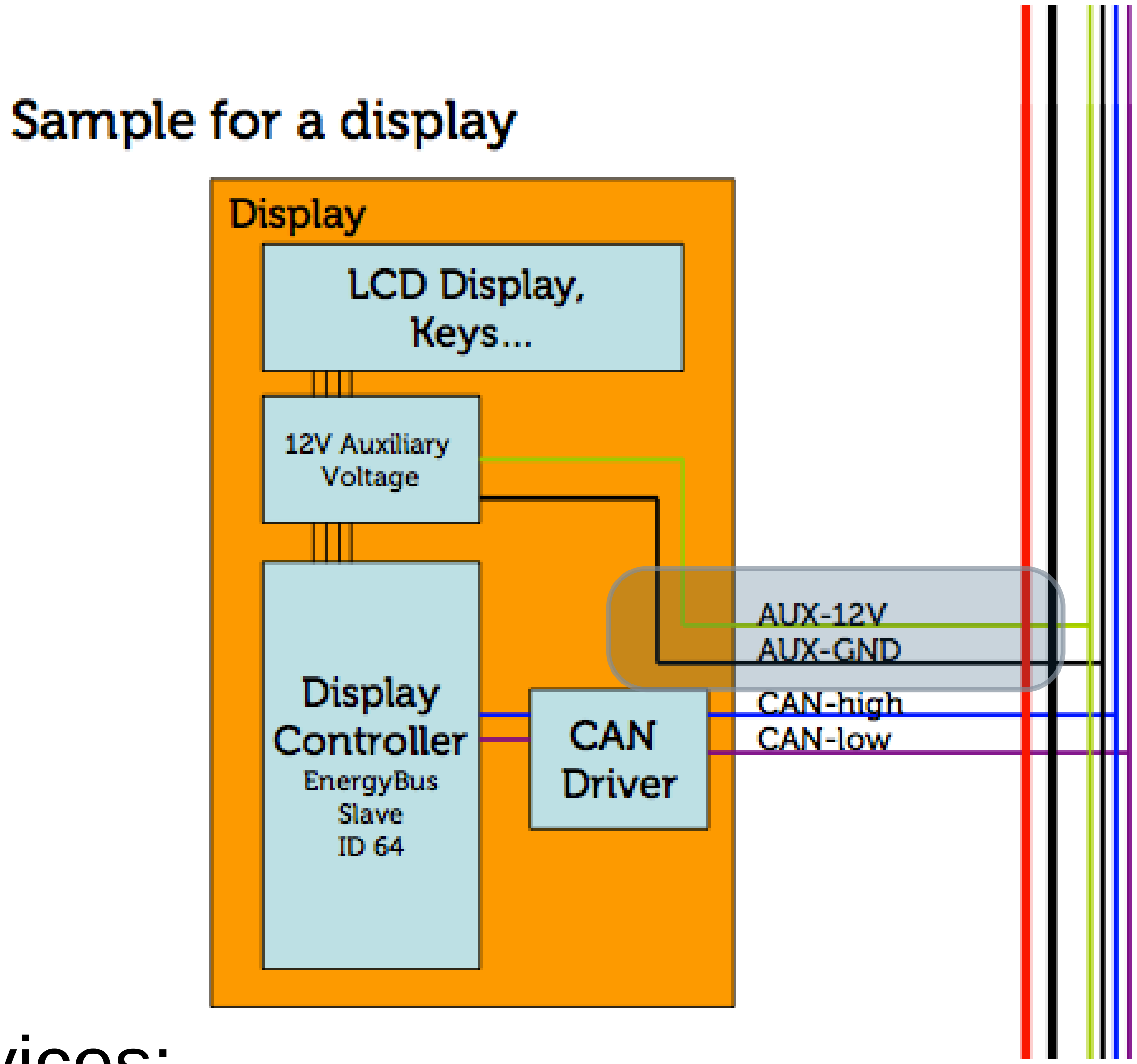
Active Devices



further active devices:

- voltage converter
- battery pack
- load monitoring unit
- generator unit
- …

Passive Devices



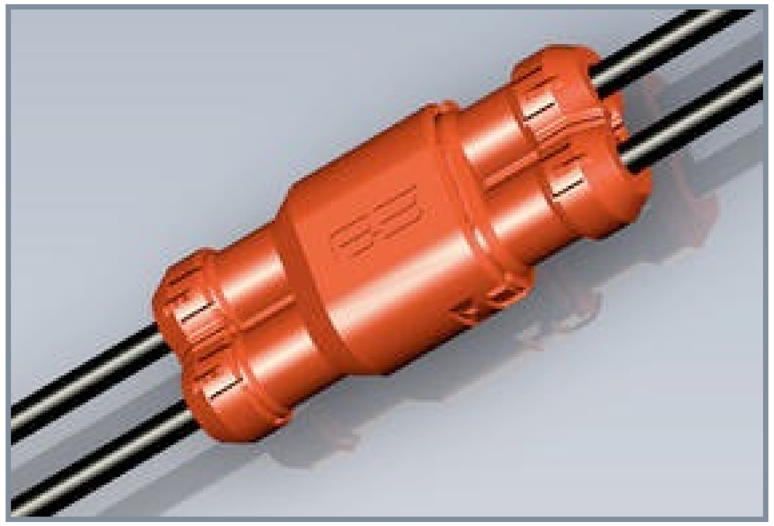
further passive devices:

- sensor unit
- gateway unit
- security unit
- manufacture specific unit
- …

EnergyBus

Hardware aspects

- family of connectors
- additional power lines (MAIN and AUX)



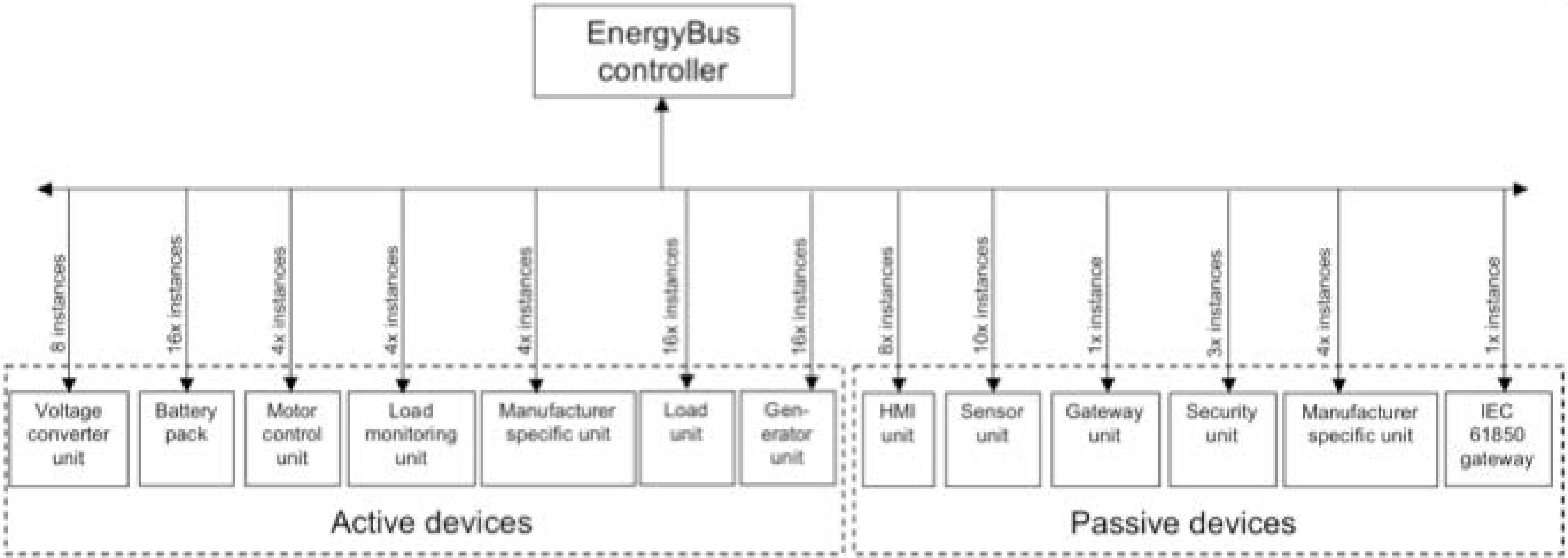
Software aspects

- protocols
- Object Directory definitions
- specific EnergyBus applications

EnergyBus Network

EnergyBus controller (EBC)

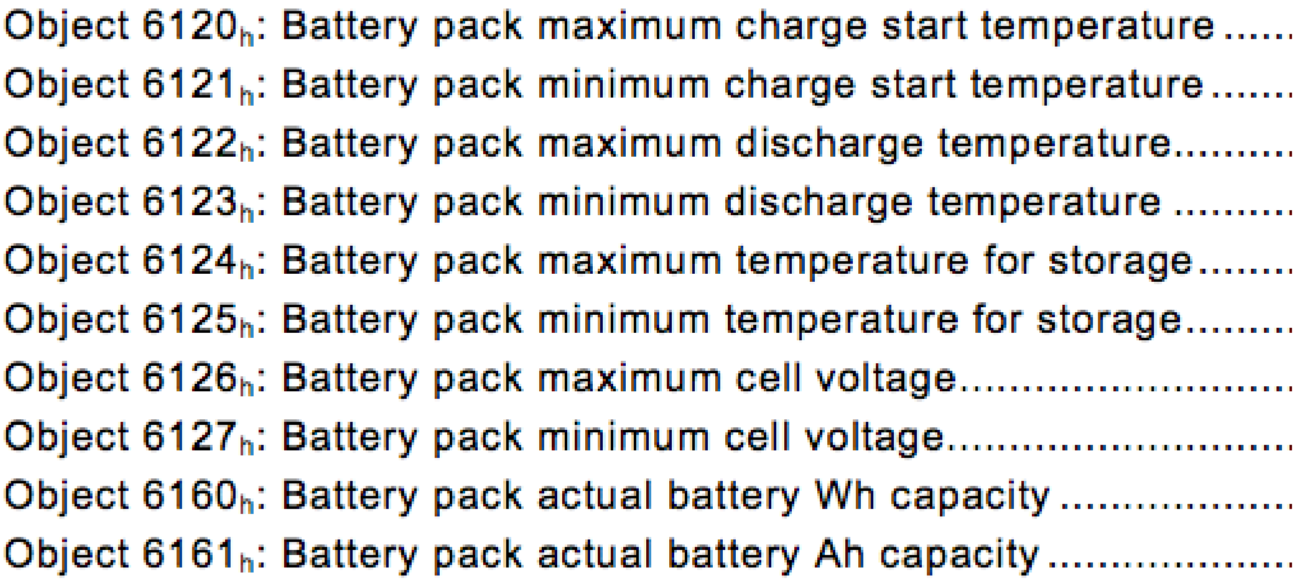
- distribution of energy
- ensures safety of the network
- monitors and controls other EMS devices
- acts as NMT and LSS Master
- maintains SDO connections to all devices
- only one activated EBC in the network
- fixed node-ID 01_h



EnergyBus Virtual Devices

- extend the Object Directory

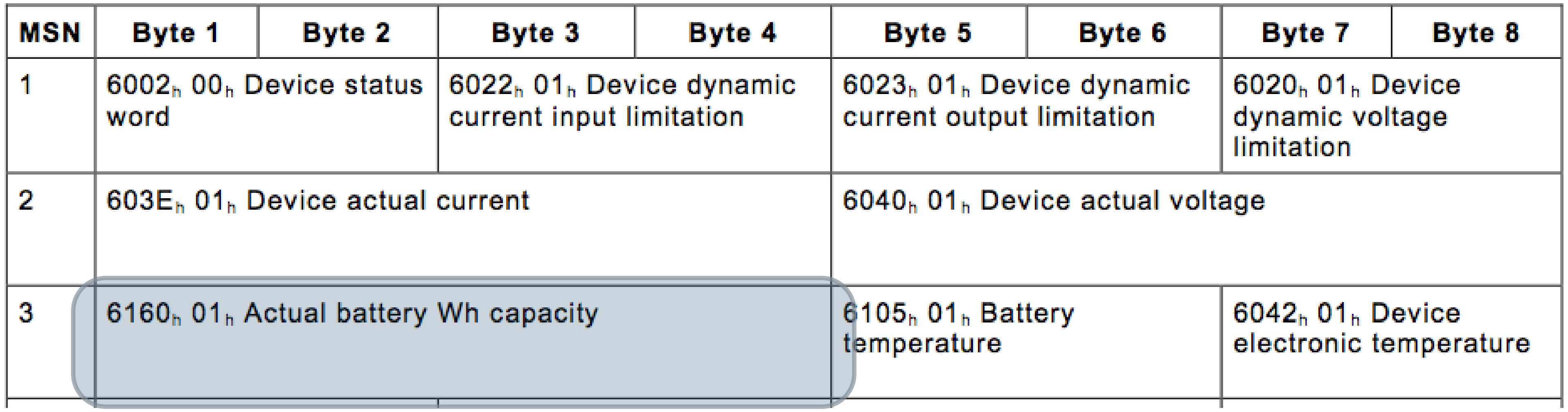
Index	Description
0000h	reserved
0001h - 025Fh	Data types
0260h - 0FFFh	reserved
1000h - 1FFFh	Communication object area
2000h - 5FFFh	Manufacturer specific area
6000h - 9FFFh	Device profile specific area
A000h - BFFFh	Interface profile specific area
C000h - FFFFh	reserved



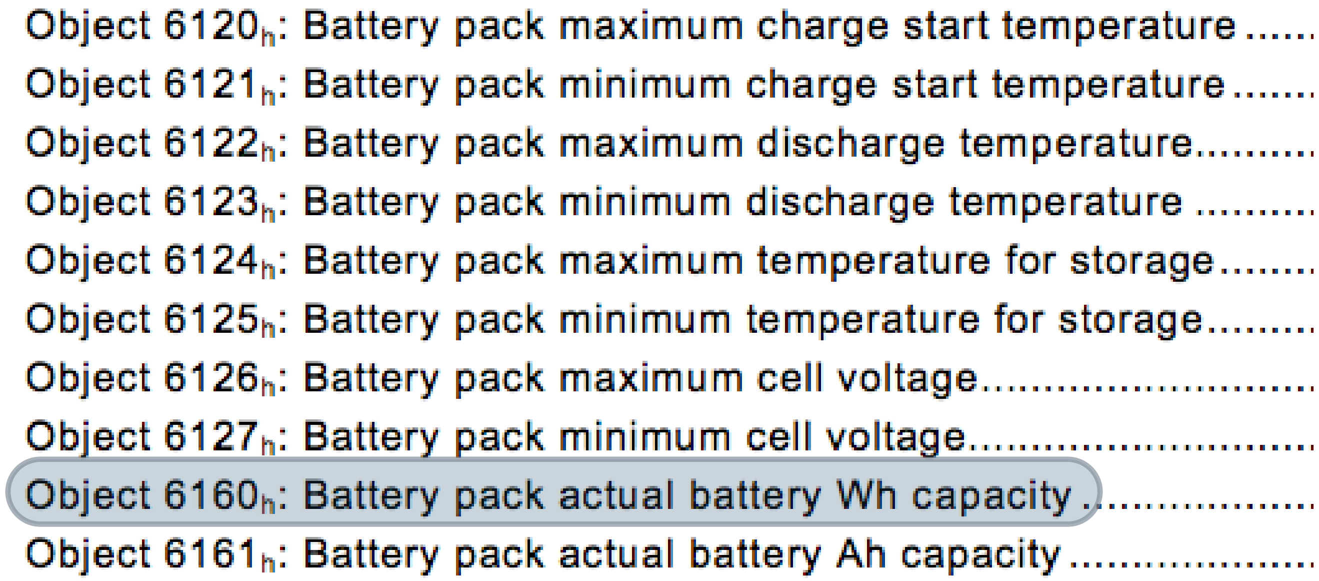
Object 6120_h: Battery pack maximum charge start temperature ......
Object 6121_h: Battery pack minimum charge start temperature ....
Object 6122_h: Battery pack maximum discharge temperature.........
Object 6123_h: Battery pack minimum discharge temperature ....
Object 6124_h: Battery pack maximum temperature for storage........
Object 6125_h: Battery pack minimum temperature for storage.........
Object 6126_h: Battery pack maximum cell voltage..........................
Object 6127_h: Battery pack minimum cell voltage...........................
Object 6160_h: Battery pack actual battery Wh capacity ....
Object 6161_h: Battery pack actual battery Ah capacity ....

EnergyBus Virtual Devices

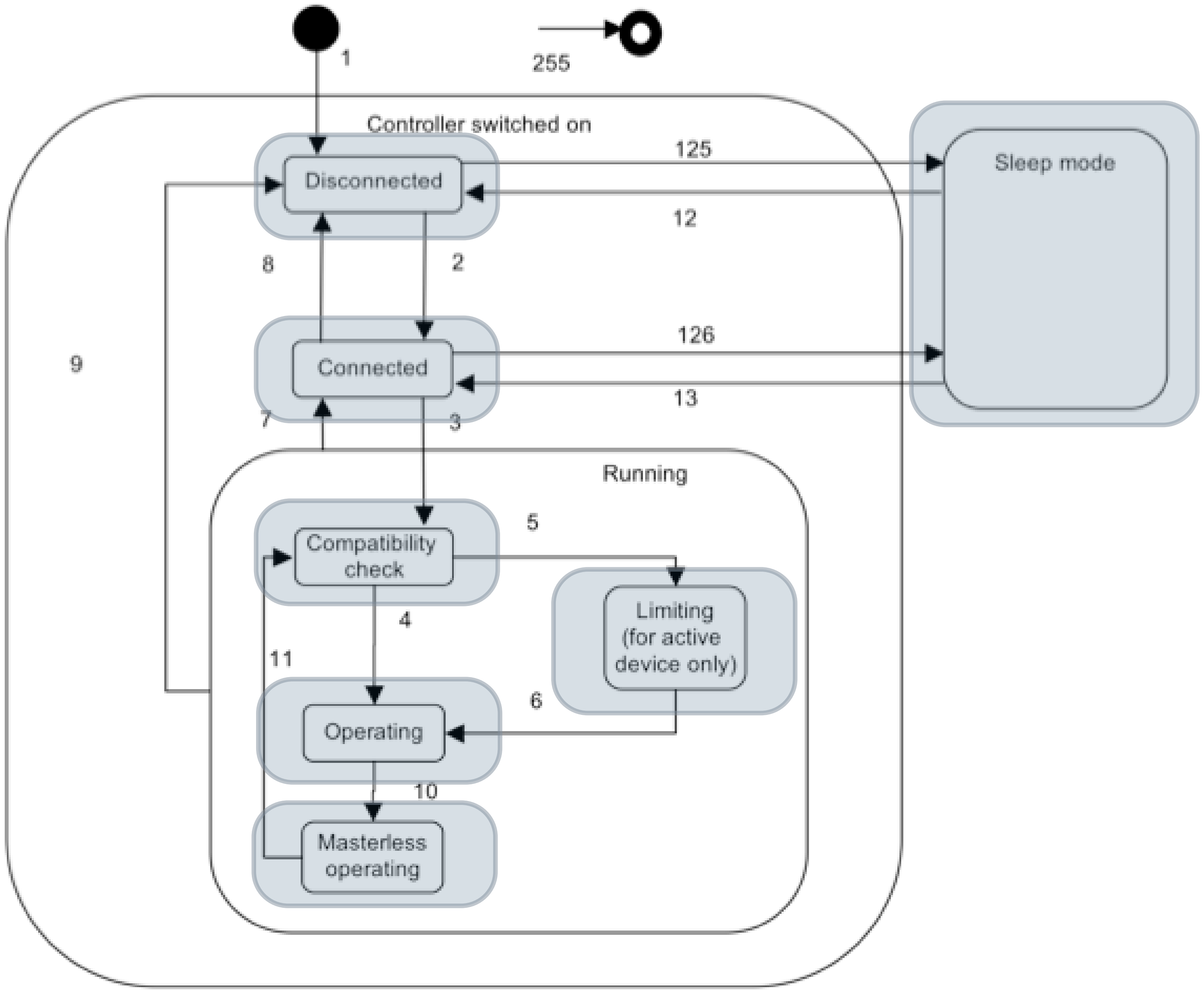
- extend the Object Directory
- predefined set of PDO messages



MSN	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8
1	6002$_h$ 00$_h$ Device status word		6022$_h$ 01$_h$ Device dynamic current input limitation		6023$_h$ 01$_h$ Device dynamic current output limitation		6020$_h$ 01$_h$ Device dynamic voltage limitation	
2	603E$_h$ 01$_h$ Device actual current				6040$_h$ 01$_h$ Device actual voltage			
3	6160$_h$ 01$_h$ Actual battery Wh capacity				6105$_h$ 01$_h$ Battery temperature		6042$_h$ 01$_h$ Device electronic temperature	



Energy Management Automaton



Disconnected:

- no power consumption
- no CAN communication

Connected:

- low power supply (CAN)
- layer setting service

Compatibility check:

- awaits EBC check

Limiting:

- adjustment of electrical parameters

Operating:

- device specific application is running

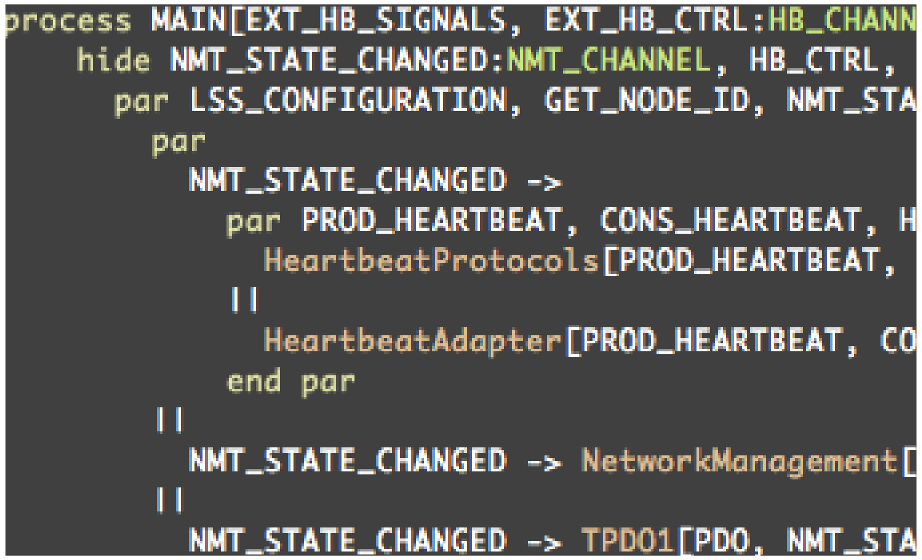
Masterless operating:

- optional, running without Master
- mandatory for stationary EMS

Sleep mode:

- energy saving mode
- Sleep Mode automaton & service

Formal Specification



```
process MAIN[EXT_HB_SIGNALS, EXT_HB_CTRL:HB_CHANN
    hide NMT_STATE_CHANGED:NMT_CHANNEL, HB_CTRL,
      par LSS_CONFIGURATION, GET_NODE_ID, NMT_STA
        par
          NMT_STATE_CHANGED ->
            par PROD_HEARTBEAT, CONS_HEARTBEAT, H
              HeartbeatProtocols[PROD_HEARTBEAT,
            ||
              HeartbeatAdapter[PROD_HEARTBEAT, CO
            end par
        ||
          NMT_STATE_CHANGED -> NetworkManagement[
        ||
          NMT_STATE_CHANGED -> TPDO1[PDO, NMT_STA
```

Formal Specification

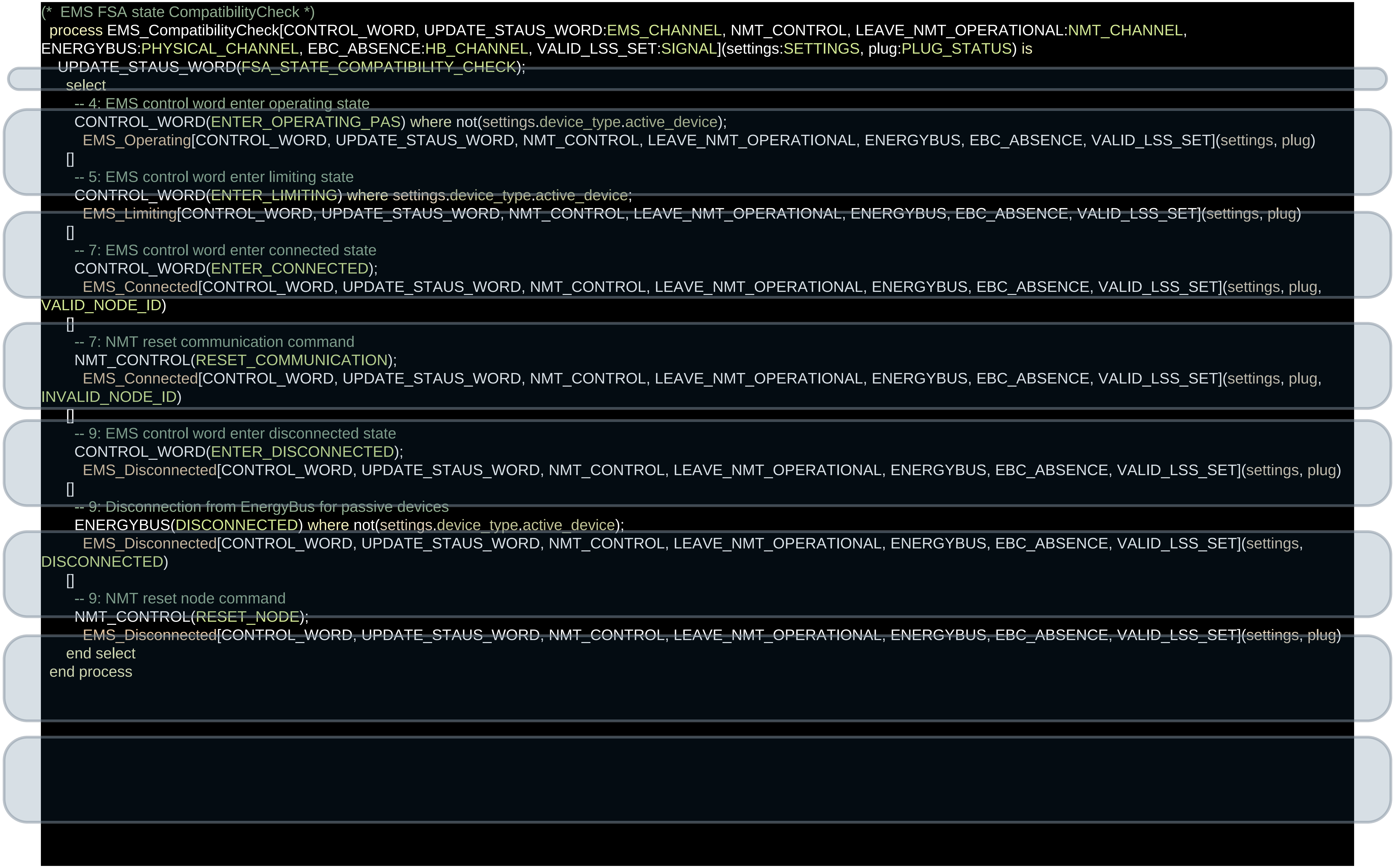
Informal documentation

- CANopen CiA 301, 302 series, 305
- EnergyBus CiA 454 series - 14 documents
- textual description
- sequence diagrams
- automata

Formal language: LNT

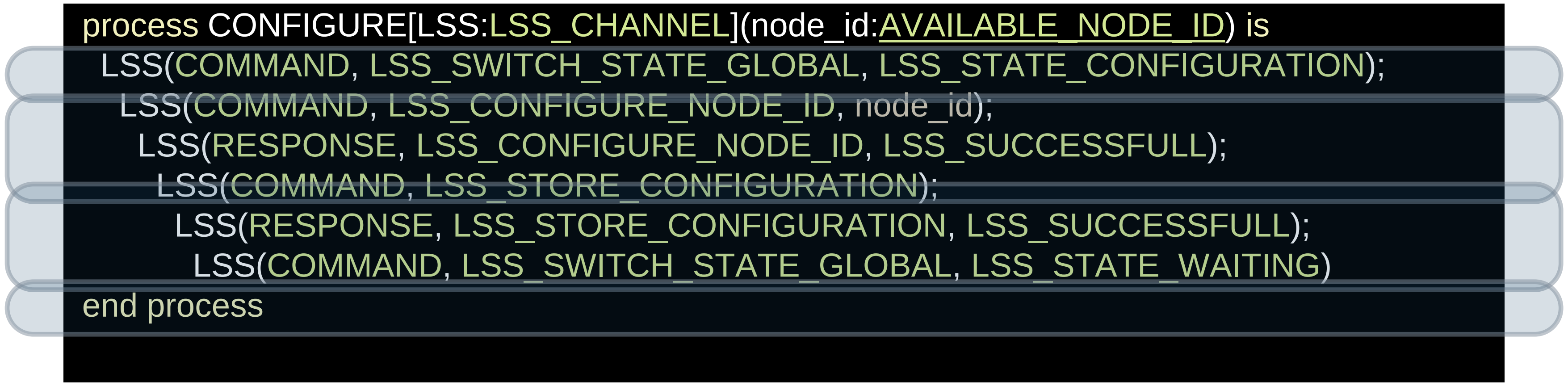
- descendent of LOTOS & E-LOTOS
- modern combination of process algebra, functional and imperative languages
- LTS semantics / SOS rules
- supported by CADP http://cadp.inria.fr

Formalization of Automata

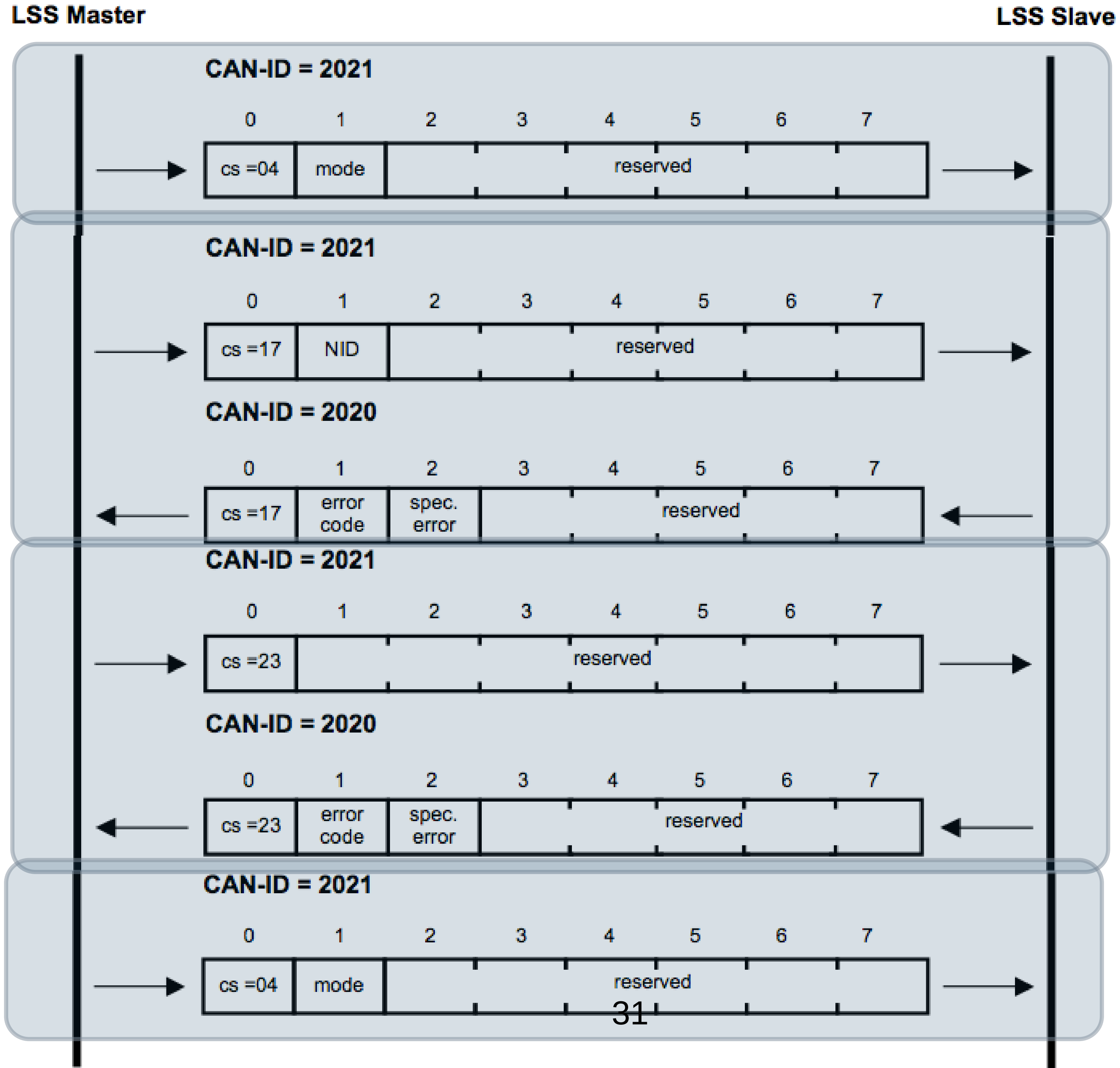


```
(*  EMS FSA state CompatibilityCheck *)
  process EMS_CompatibilityCheck[CONTROL_WORD, UPDATE_STAUS_WORD:EMS_CHANNEL, NMT_CONTROL, LEAVE_NMT_OPERATIONAL:NMT_CHANNEL,
ENERGYBUS:PHYSICAL_CHANNEL, EBC_ABSENCE:HB_CHANNEL, VALID_LSS_SET:SIGNAL](settings:SETTINGS, plug:PLUG_STATUS) is
    UPDATE_STAUS_WORD(FSA_STATE_COMPATIBILITY_CHECK);
      select
        -- 4: EMS control word enter operating state
        CONTROL_WORD(ENTER_OPERATING_PAS) where not(settings.device_type.active_device);
          EMS_Operating[CONTROL_WORD, UPDATE_STAUS_WORD, NMT_CONTROL, LEAVE_NMT_OPERATIONAL, ENERGYBUS, EBC_ABSENCE, VALID_LSS_SET](settings, plug)
      []
        -- 5: EMS control word enter limiting state
        CONTROL_WORD(ENTER_LIMITING) where settings.device_type.active_device;
          EMS_Limiting[CONTROL_WORD, UPDATE_STAUS_WORD, NMT_CONTROL, LEAVE_NMT_OPERATIONAL, ENERGYBUS, EBC_ABSENCE, VALID_LSS_SET](settings, plug)
      []
        -- 7: EMS control word enter connected state
        CONTROL_WORD(ENTER_CONNECTED);
          EMS_Connected[CONTROL_WORD, UPDATE_STAUS_WORD, NMT_CONTROL, LEAVE_NMT_OPERATIONAL, ENERGYBUS, EBC_ABSENCE, VALID_LSS_SET](settings, plug,
VALID_NODE_ID)
      []
        -- 7: NMT reset communication command
        NMT_CONTROL(RESET_COMMUNICATION);
          EMS_Connected[CONTROL_WORD, UPDATE_STAUS_WORD, NMT_CONTROL, LEAVE_NMT_OPERATIONAL, ENERGYBUS, EBC_ABSENCE, VALID_LSS_SET](settings, plug,
INVALID_NODE_ID)
      []
        -- 9: EMS control word enter disconnected state
        CONTROL_WORD(ENTER_DISCONNECTED);
          EMS_Disconnected[CONTROL_WORD, UPDATE_STAUS_WORD, NMT_CONTROL, LEAVE_NMT_OPERATIONAL, ENERGYBUS, EBC_ABSENCE, VALID_LSS_SET](settings, plug)
      []
        -- 9: Disconnection from EnergyBus for passive devices
        ENERGYBUS(DISCONNECTED) where not(settings.device_type.active_device);
          EMS_Disconnected[CONTROL_WORD, UPDATE_STAUS_WORD, NMT_CONTROL, LEAVE_NMT_OPERATIONAL, ENERGYBUS, EBC_ABSENCE, VALID_LSS_SET](settings,
DISCONNECTED)
      []
        -- 9: NMT reset node command
        NMT_CONTROL(RESET_NODE);
          EMS_Disconnected[CONTROL_WORD, UPDATE_STAUS_WORD, NMT_CONTROL, LEAVE_NMT_OPERATIONAL, ENERGYBUS, EBC_ABSENCE, VALID_LSS_SET](settings, plug)
      end select
  end process
```

Formalization of Sequence Diagrams



```
process CONFIGURE[LSS:LSS_CHANNEL](node_id:AVAILABLE_NODE_ID) is
 LSS(COMMAND, LSS_SWITCH_STATE_GLOBAL, LSS_STATE_CONFIGURATION);
  LSS(COMMAND, LSS_CONFIGURE_NODE_ID, node_id);
   LSS(RESPONSE, LSS_CONFIGURE_NODE_ID, LSS_SUCCESSFULL);
    LSS(COMMAND, LSS_STORE_CONFIGURATION);
     LSS(RESPONSE, LSS_STORE_CONFIGURATION, LSS_SUCCESSFULL);
      LSS(COMMAND, LSS_SWITCH_STATE_GLOBAL, LSS_STATE_WAITING)
end process
```



0	1	2	3	4	5	6	7
cs =04	mode	reserved					

0	1	2	3	4	5	6	7
cs =17	NID	reserved					

0	1	2	3	4	5	6	7
cs =17	error code	spec. error	reserved				

0	1	2	3	4	5	6	7
cs =23	reserved						

0	1	2	3	4	5	6	7
cs =23	error code	spec. error	reserved				

0	1	2	3	4	5	6	7
cs =04	mode	reserved					

Specification Effort

Component	Documentation (pages)	LNT code (lines)
NMT	8	260
Heartbeat	6	200
EMCY/Error	4	145
LSS	62	360
EMS	3	440
PDO	45	60
SDO	25	30
OD/Variables	(300)	70

Time spent: 6 months

- including progression of the EnergyBus specification
- including model abstractions

Specification Issues Detected

Issue 1:

ambiguities in the Node-ID configuration in LSS v2

➡ when is a node-ID temporarily / persistently stored?

Issue 2:

insufficient specification of Sleep Mode

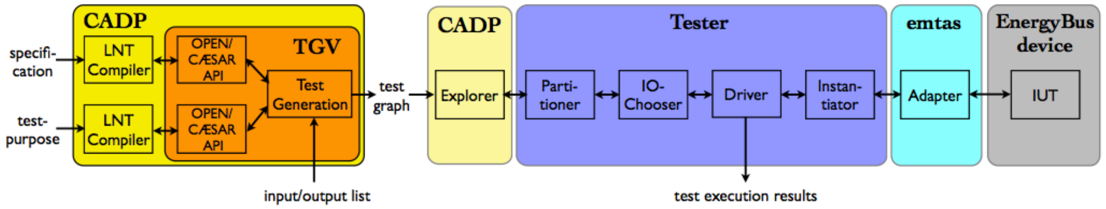
➡ interferences with NMT competence

➡ unclear definition of involved messages / events

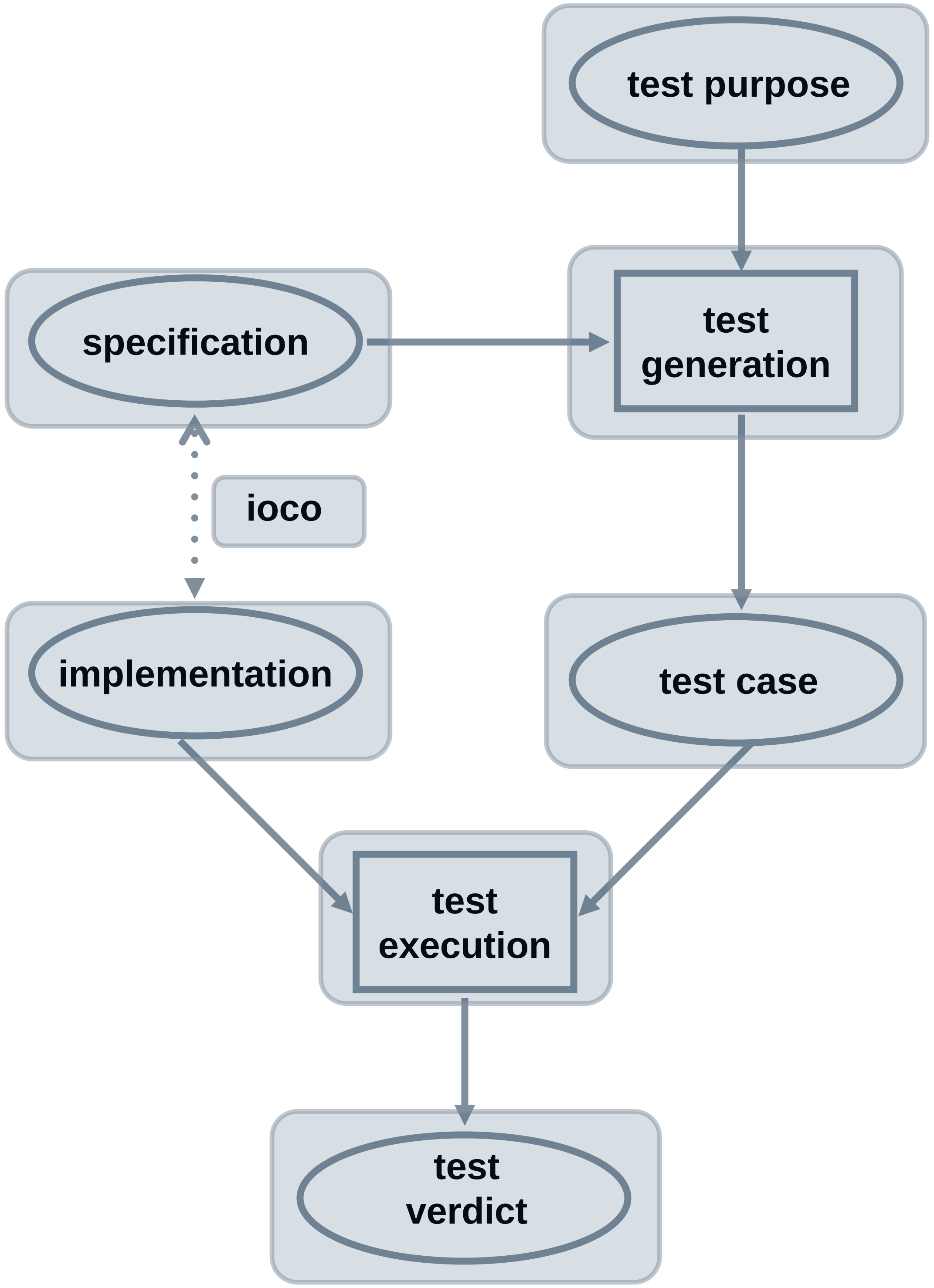
Issue 3:

confusing and non-consistent naming in new documents

Certification Framework

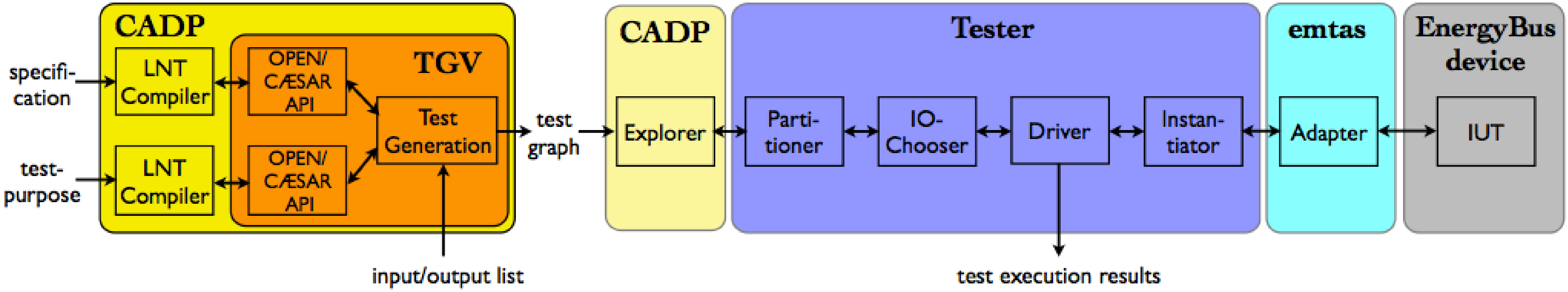


Model-based Testing



- **implementation:**
  - Implementation Under Test (IUT) is real object
  - assume existence of formal model
- **specification:**
  - formal model of correct behavior
- **input-output conformance relation:**
  - defines condition for correct implementation
- **test purpose:**
  - formal model of relevant application scenario
- **test generation:**
  - automatic derivation of test cases
- **test cases:**
  - experiment description as formal model
- **test execution:**
  - execute experiment
- **test verdict:**
  - **pass**, **fail**, **inconclusive**

Tool Setup



Offline:

- input: specification, test purpose as .lnt
- input/output list for turning LTS into IOLTS
- test graph generation by TGV [INRIA Rennes]
- output as .bcg

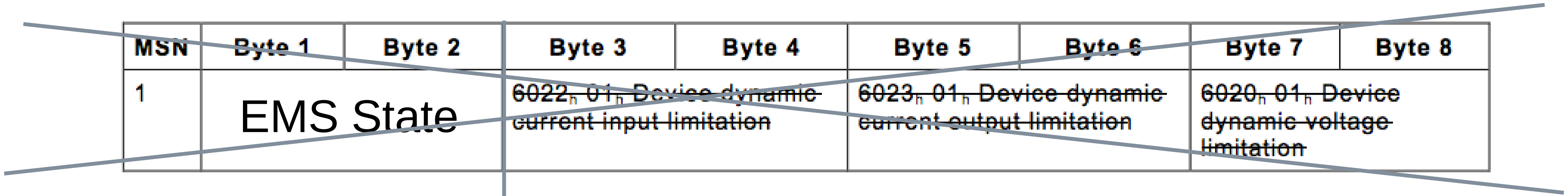
Online:

- on-the-fly derivation of virtual test case
- provides input/receives output via C-Library from **emtas**
- output: test verdict, run log as .txt

Fighting State-Space Explosion

combined approaches:

- on-the-fly algorithms of the OPEN/CÆSAR API
- data abstraction
  - qualitative: two-valued information
  - relative: three-valued information
- functional abstraction
  - focus on important data
  - focus on needed protocol parts

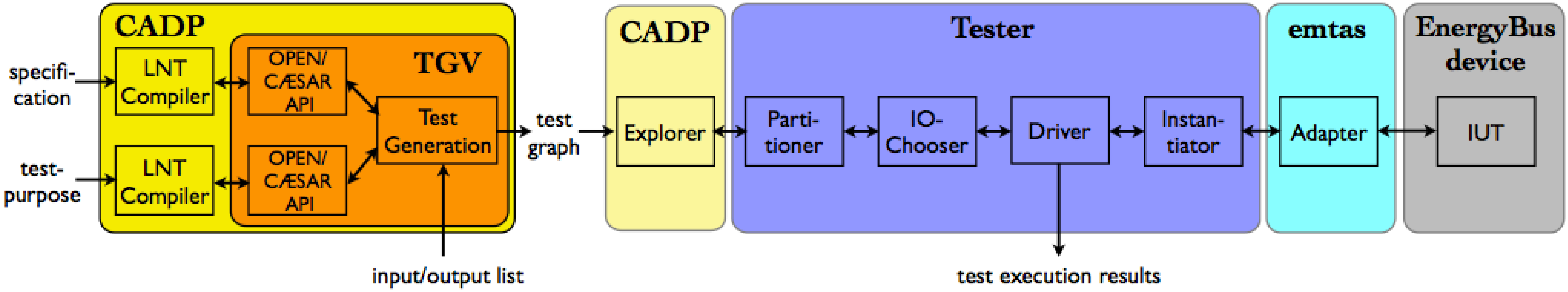


MSN	Byte 1	Byte 2	Byte 3	Byte 4	Byte 5	Byte 6	Byte 7	Byte 8
1	EMS State		~~6022$_h$, 01$_h$ Device dynamic current input limitation~~		~~6023$_h$, 01$_h$ Device dynamic current output limitation~~		~~6020$_h$, 01$_h$ Device dynamic voltage limitation~~	

LIMITATION / NO_LIMITATION

DECREASE_LIMIT / NO_CHANGE / INCREASE_LIMIT

Applied Tests



Test purposes:

- different initializations of unconfigured devices
- boot-up procedure and on-line PDO transmission of configured devices
- simple scenarios
- 80 lines LNT vs. test graph 600 states / 1100 transitions

IUT:

- sample C applications
- based on the emtas CANopen C-Library
- running on a Linux workstation
- plugged to Tester via CAN connection

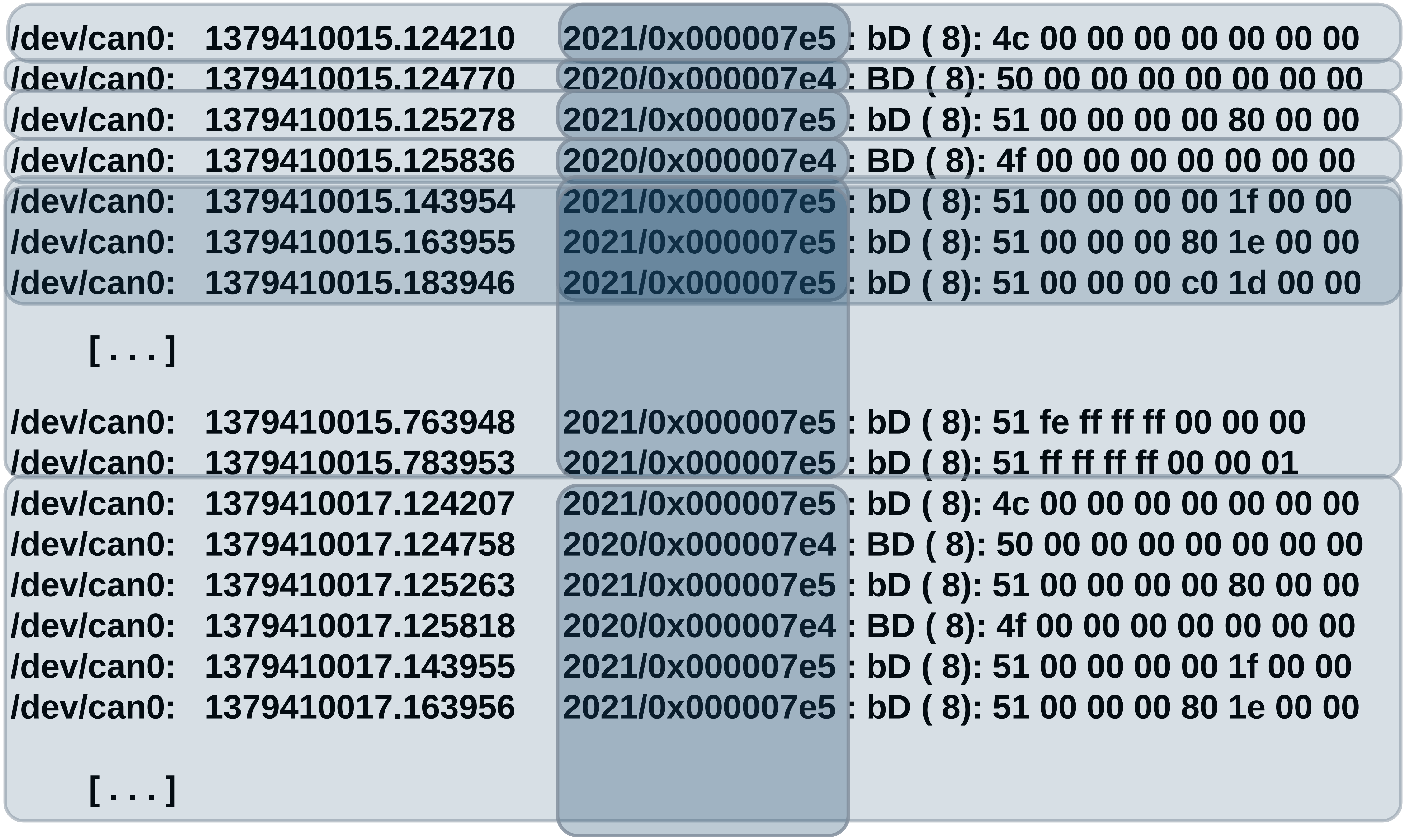
Issue #1 Found in the CANopen Layer

Missing data part of SYNC message

```
/dev/can0:   1371475223.952977    1794/0x00000702 : bD ( 1): 05
/dev/can0:   1371475224.052980    1794/0x00000702 : bD ( 1): 05
/dev/can0:   1371475224.153015    1794/0x00000702 : bD ( 1): 7f
/dev/can0:   1371475224.198949     128/0x00000080 : BD ( 0):
/dev/can0:   1371475224.199208    1793/0x00000701 : BD ( 1): 7f
/dev/can0:   1371475224.252981    1794/0x00000702 : bD ( 1): 7f
/dev/can0:   1371475224.352985    1794/0x00000702 : bD ( 1): 7f
/dev/can0:   1371475224.452983    1794/0x00000702 : bD ( 1): 7f
```

Issue #2 Found in the CANopen Layer

Livelock in LSS Fastscan service

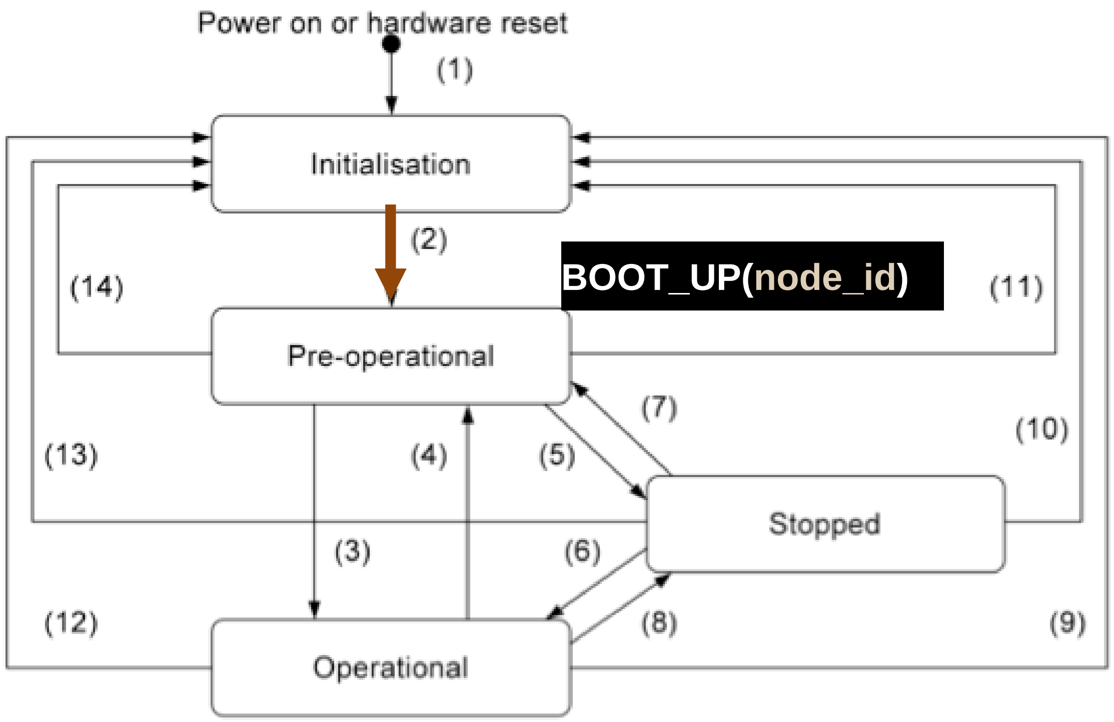


```
/dev/can0:   1379410015.124210    2021/0x000007e5 : bD ( 8): 4c 00 00 00 00 00 00 00
/dev/can0:   1379410015.124770    2020/0x000007e4 : BD ( 8): 50 00 00 00 00 00 00 00
/dev/can0:   1379410015.125278    2021/0x000007e5 : bD ( 8): 51 00 00 00 00 80 00 00
/dev/can0:   1379410015.125836    2020/0x000007e4 : BD ( 8): 4f 00 00 00 00 00 00 00
/dev/can0:   1379410015.143954    2021/0x000007e5 : bD ( 8): 51 00 00 00 00 1f 00 00
/dev/can0:   1379410015.163955    2021/0x000007e5 : bD ( 8): 51 00 00 00 80 1e 00 00
/dev/can0:   1379410015.183946    2021/0x000007e5 : bD ( 8): 51 00 00 00 c0 1d 00 00

        [ . . . ]

/dev/can0:   1379410015.763948    2021/0x000007e5 : bD ( 8): 51 fe ff ff ff 00 00 00
/dev/can0:   1379410015.783953    2021/0x000007e5 : bD ( 8): 51 ff ff ff ff 00 00 01
/dev/can0:   1379410017.124207    2021/0x000007e5 : bD ( 8): 4c 00 00 00 00 00 00 00
/dev/can0:   1379410017.124758    2020/0x000007e4 : BD ( 8): 50 00 00 00 00 00 00 00
/dev/can0:   1379410017.125263    2021/0x000007e5 : bD ( 8): 51 00 00 00 00 80 00 00
/dev/can0:   1379410017.125818    2020/0x000007e4 : BD ( 8): 4f 00 00 00 00 00 00 00
/dev/can0:   1379410017.143955    2021/0x000007e5 : bD ( 8): 51 00 00 00 00 1f 00 00
/dev/can0:   1379410017.163956    2021/0x000007e5 : bD ( 8): 51 00 00 00 80 1e 00 00

        [ . . . ]
```

Issue #3 Found in the CANopen Layer

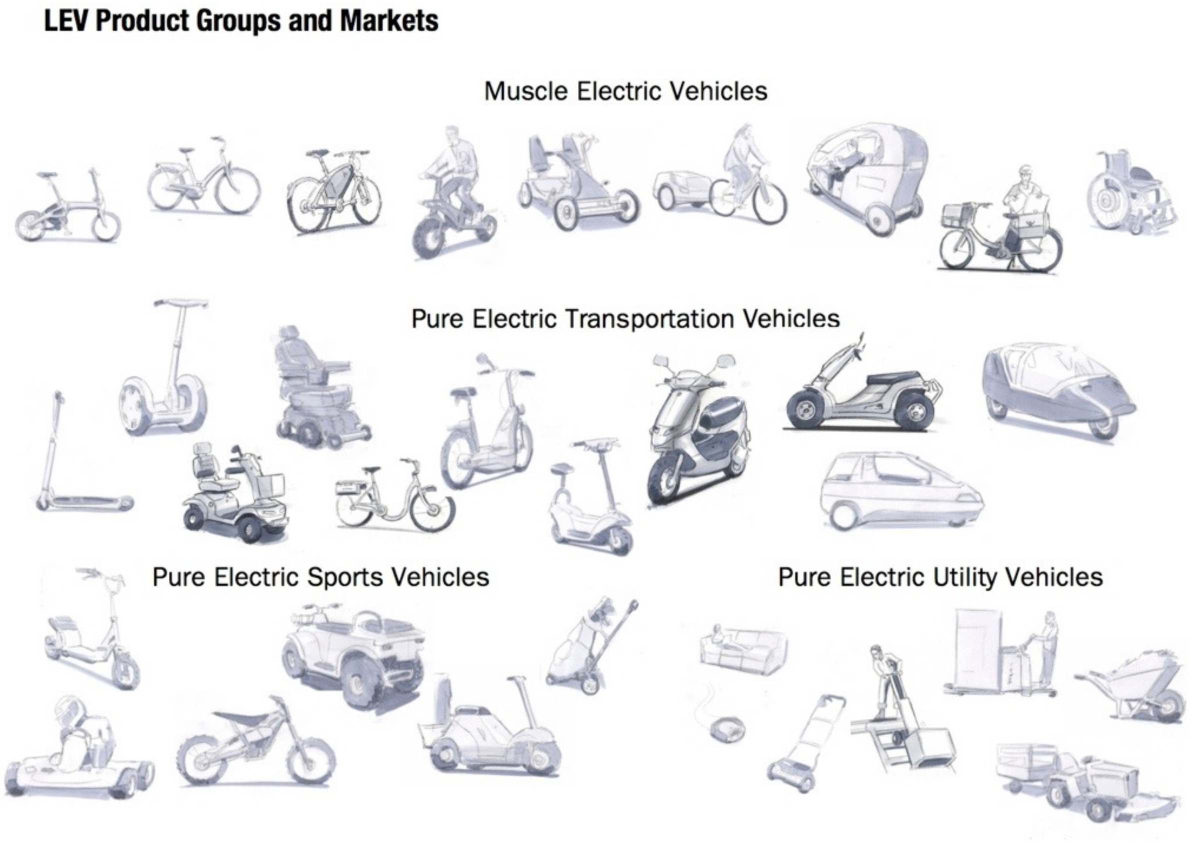
Missing state change during LSS configuration

```
process CONFIGURE[LSS:LSS_CHANNEL](node_id:AVAILABLE_NODE_ID) is
  LSS(COMMAND, LSS_SWITCH_STATE_GLOBAL, LSS_STATE_CONFIGURATION);
    LSS(COMMAND, LSS_CONFIGURE_NODE_ID, node_id);
      LSS(RESPONSE, LSS_CONFIGURE_NODE_ID, LSS_SUCCESSFULL);
        LSS(COMMAND, LSS_STORE_CONFIGURATION);
          LSS(RESPONSE, LSS_STORE_CONFIGURATION, LSS_SUCCESSFULL);
            LSS(COMMAND, LSS_SWITCH_STATE_GLOBAL, LSS_STATE_WAITING)
end process
```



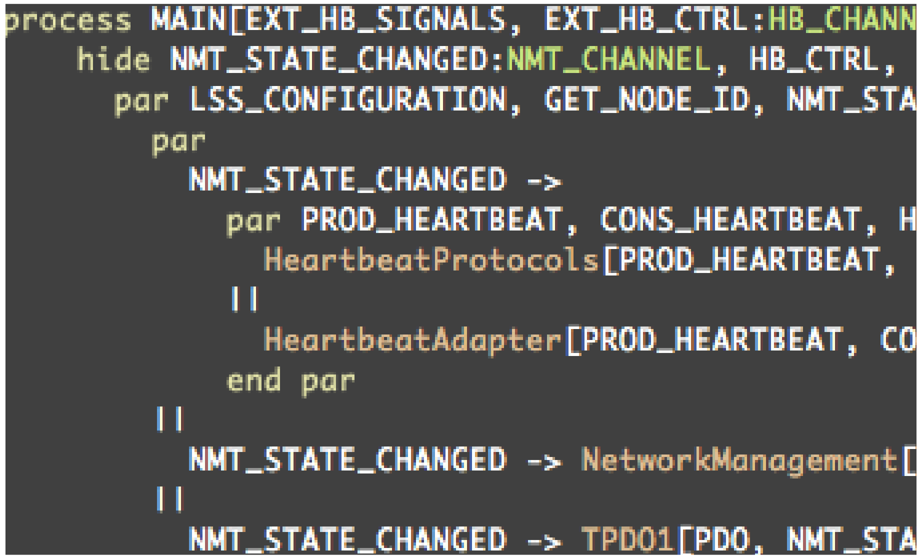
Conclusion

Energy Management Systems are increasingly relevant


LEV Product Groups and Markets
Muscle Electric Vehicles
Pure Electric Transportation Vehicles
Pure Electric Sports Vehicles
Pure Electric Utility Vehicles

Conclusion

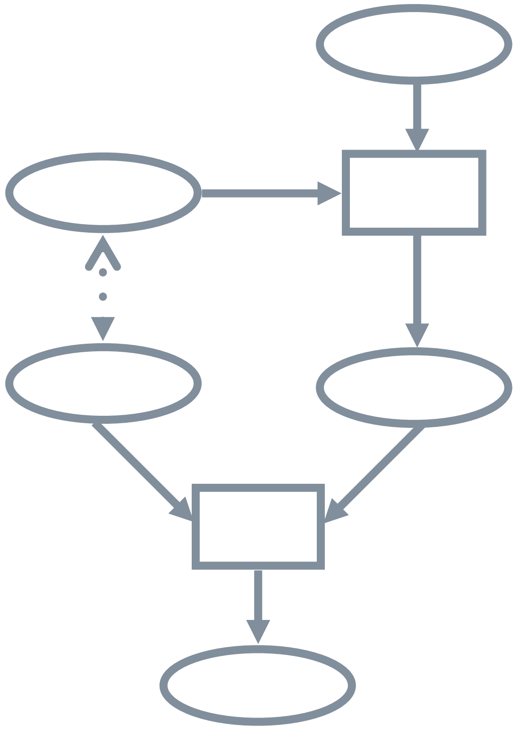
- Formal specification:
  - a sound basis for verification techniques
  - EnergyBus documentation issues found

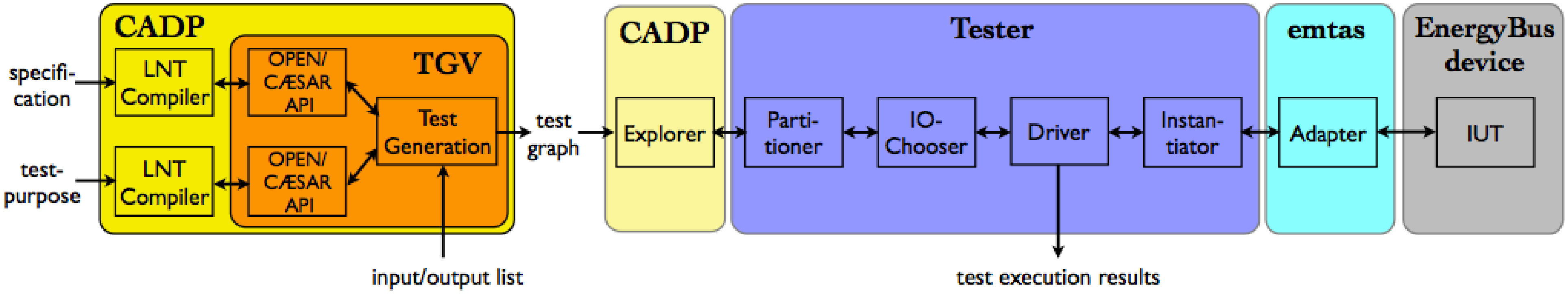


```
process MAIN[EXT_HB_SIGNALS, EXT_HB_CTRL:HB_CHANN
    hide NMT_STATE_CHANGED:NMT_CHANNEL, HB_CTRL,
      par LSS_CONFIGURATION, GET_NODE_ID, NMT_STA
        par
          NMT_STATE_CHANGED ->
            par PROD_HEARTBEAT, CONS_HEARTBEAT, H
              HeartbeatProtocols[PROD_HEARTBEAT,
            ||
              HeartbeatAdapter[PROD_HEARTBEAT, CO
            end par
        ||
          NMT_STATE_CHANGED -> NetworkManagement[
        ||
          NMT_STATE_CHANGED -> TPDO1[PDO, NMT_STA
```

Conclusion

- A certification framework for the EnergyBus:
  - Model-based testing
  - Tool setup
  - Three issues detected in the CANopen layer





Future Work

- Extending the formal model
  - **Charging Protocol**
  - power-related model components
  - virtual devices
- Further approaches against state-space explosion
  - abstract from CANopen layer
  - compositional model reductions based on bisimulations
  - TGV successor supporting online test case generation [INRIA]
  - **motest:** online model-based tester [Saarland University]
- Applying further verification techniques