Modelling and verifying IEEE Std 11073-20601 session setup using mCRL2

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Modelling and verifying
IEEE Std 11073-20601 session setup using mCRL2

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Abstract. In this paper we advocate that formal verification should be a part of the development of a communication standard; in a short period of time issues are uncovered that have been in the standard for a number of years, and all subtleties in the correctness of the protocol are understood.

We model and verify the session setup protocol that is part of the IEEE 11073-20601:2008 standard for communication between personal health devices. We identify a number of issues present in the standards document. Discussion with a member of the standards committee unveiled that most, but not all, of the identified issues are fixed in the IEEE 11073-20601:2010 version of the standard. In addition, the correctness of the protocol, including the fixes, is assessed. For this, properties of the session setup protocol are formulated, and using the model checker mCRL2 it is verified whether the model satisfies these properties. We show that the session setup protocol is flawed, and propose a straightforward way to fix this issue.

Keywords. Verification, model checking, IEEE 11073-20601, protocol standardisation, interoperability

1 Introduction

Communication standards often prescribe an exchange protocol [MGWB03,?]. These protocols form the basis of development and testing of the communication of, sometimes critical, devices. Errors in these standards often lead to high costs in the development of such devices, and introduce safety threats in them [BB01]. Standards might even obstruct a solution for these errors, because a fixed version of the protocol does not conform to the standard any more, and may break backwards compatibility.

IEEE 11073 forms a family of such standards for device communication, supporting a high level of automation—the user only needs to connect the devices, everything else is automatic. Within this family, the IEEE 11073-20601 standard focuses on personal telehealth devices. Examples of such devices are heart rate watches, glucose monitoring devices, and weighing scales.

IEEE 11073-20601 defines a generic data exchange protocol for these personal telehealth devices. It is geared towards allowing devices, called agents, to transfer patient specific health data to a manager with a low overhead. Devices allow a large number of different configurations. In case of a weighing scale, the configuration can, e.g., determine whether transferred weight data must be interpreted as kilogrammes or pounds.

Within the data exchange protocol described in IEEE 11073-20601 we can roughly identify two phases. In the session setup phase, an agent and a manager negotiate a configuration, in the second phase, measurement data is exchanged. The session setup protocol has to ensure that the agent and the manager are using the same configuration before measurement data is successfully communicated.

In this paper we only consider the session setup phase. This is motivated by the apparent importance of the session setup in the standard. The importance is indicated by the effort spent in describing session setup using a combination of UML state machines [Obj09], message sequence charts [Obj09], state transition tables and natural language. For other parts of the protocol one or more of these descriptions have been omitted.

The quality of the standard and the added value of formal techniques are assessed in the following three stages:
1. We assess understandability, consistency, and completeness of the 2008 version of the standard [IEE08]. An initial model of this version of the standard is [IEE08] constructed in the language mCRL2 [GMR+08], which is an ACP [BK84] style process algebra with an accompanying verification toolset. At the time of the initial modelling a preliminary version of the 2010 update of the standard [IEE10] was under development, but not available to the authors of this paper. During this first stage, we uncovered a number of issues in the standards document in a matter of hours. These issues have been present in the standard since 2008. Subsequent discussion of the issues with a member of the standards committee showed that most, but not all, of the problems we discovered have been fixed in the 2010 version of the standard [IEE10]. As far as we are aware, we found all issues regarding the correctness of session setup that were fixed in the 2010 version of the standard.

2. We investigate whether the session setup protocol is correct. We incorporate the fixes of the 2010 version of the standard, as well as our own observations from the first stage, into the mCRL2 model. We first formulate a number of correctness requirements. The requirements for session-setup are not clearly documented in the standard, but the requirements that we verify have been validated with a member of the standards committee. The mCRL2 model is verified using modal $\mu$-calculus formulae. We show that there is a subtle race condition in the protocol as it is described by the standard. This can lead to transmission of measurement data in a situation where an agent and manager are using different configurations.

3. We propose a straightforward fix for the problem we find in the previous stage. We verify the fixed protocol, and show that it guarantees that the agent and the manager use consistent configurations if measurements are transferred.

Our experiment confirms that formal modelling and verification form a useful addition to the standardisation process, even if the standard already employs some formal techniques for describing protocols. Protocol standards are susceptible to inconsistencies and incompleteness. Furthermore, unverified protocols are likely to contain subtle, hard to detect bugs, that are costly to fix once the standard has been released, if fixing is possible at all without breaking standard compliance.

**Related work** Several medical protocol standards have been studied in the literature. Among others the ISO/IEEE 1073.2 standard for remote control [MG05,7]. Besides medical protocols, other standard protocols have been studied extensively. Examples are the IEEE 1394 firewire standard [DGRV00,?], contention resolution in the ZigBee protocol [Fru06], and the Carrier Sense Multiple Access/Collision Detection protocol in IEEE 802.3 [DFH+05].

Several case studies have been carried out showing the applicability of the model checker $\mu$CRL and its successor mCRL2. Among others an automated parking garage [MP07], a distributed system for lifting trucks [GPW03] as well as a printer intended to operate in the manufacturing of printed circuit boards [SR09] have been verified. The translation of UML state charts to mCRL2 that we use was described in [HKL+09].

**Outline** The rest of this paper is structured as follows. In Section 2 we provide some background on the formalisms used. Consequently, in Section 3 we provide a more in-depth background of the verification problem at hand, explain how this has been modelled in mCRL2, and discuss the quality of the standard. In Section 4 we verify the session setup protocol. The bug that we find is fixed in Section 5. Our conclusions and recommendations are presented in Section 6.

### 2 Preliminaries

Many real-life systems are concurrent. In a concurrent system, several processes run in parallel, either on the same hardware, or on different hardware. Processes communicate or interact with each other, and with their environment, to accomplish complex tasks. Communication between such processes can either be synchronous (sending and receiving happen at the same moment), or asynchronous (sending and receiving happen at different moments).
Various languages have been proposed for describing concurrent systems. These languages include state charts [Har87], Petri nets [Pet62] and process algebras [BBR10]. These languages allow describing the behaviour at a higher level of abstraction than programming languages. As such, the languages can be viewed as specification languages. Studying a system based on a high-level specification allows analysing a conceptual view of the system, without having to cope with all implementation details.

The session setup phase of the protocol is described using state charts. For the analysis we use the specification language mCRL2 [GMR+08]. We briefly describe these formalisms and their translation in the rest of this section. The translation of the session setup is discussed in detail in Section 3.

**State machines** We assume some familiarity with UML state machines. For a detailed exposition of UML state machines we refer to [Obj09]. In this paper we use state machines that contain composite states (OR-states) and initial states. Transitions are labelled by a trigger and an action, both of which are optional. Triggers can be signals or change events. Signal events are communicated asynchronously, and can either be sent by the system, or by the environment. A change event is triggered when a certain condition becomes true. In Section 3 we introduce state machines in more detail, using part of the agent state machine as an example.

**mCRL2** The language mCRL2 is based on the process algebra ACP [BK84], extended to include data and time. A fundamental concept in mCRL2 is the process. Processes can perform actions, and be combined into new process using algebraic operators. Systems usually consist of several processes in parallel. The language mCRL2 is supported by a tool set for the analysis of mCRL2 models.

Processes can carry data as parameters. The state of the process is a combination of values of the parameters. The actions that the process can perform may be influenced by this state, and the execution of actions may result in state changes. Every process has a corresponding state machine, or Labelled Transition System, which contains all states that the process can reach, along with the transitions between the states.

A central notion in the verification process using mCRL2 is the linear process (LPS). An LPS represents a process in which all parallelism has been removed, resulting in a series of condition, action, effect rules. Model checking is performed using parameterised Boolean equation systems (PBES) [GW05]. Given an LPS and a formula expressing a requirement of the process, a PBES is generated. The solution to this PBES indicates whether the formula holds on the process. ¹

**Translation** A systematic translation of executable UML (xUML), which contains UML state machine as a subset, was described by Hansen et al. [HKL+09]. We use the translation described in *ibid* to translate the state machines of the agent and manager processes to mCRL2. Note that we assume atomic run-to-completion, which means that, while a state machine is executing a local step, no event can be dispatched to any of the state machines in the system. A translation of part of the session setup protocol is provided in Section 3.

**Modal µ-calculus** We describe requirements in a variant of the modal µ-calculus, extended with regular expressions and data [GM99]. We use the following subset of this modal µ-calculus:

\[
\begin{align*}
\varphi, \psi & ::= b \mid \nu X. \varphi \mid \langle q \rangle \varphi \mid [q] \varphi \mid \varphi \land \psi \mid \neg \varphi \\
q & ::= \alpha \mid q \cdot q \mid q^* \\
\alpha & ::= \text{true} \mid a(d) \mid \exists d : D \alpha \mid \alpha \cup \alpha \mid \neg \alpha
\end{align*}
\]

Here \( \varphi \) represents a property, \( q \) represents a set of sequences of actions, and \( \alpha \) represents a set of multi-actions. The set of all multi-actions is denoted by \( \text{true} \). Data can be introduced into a set of actions using existential quantification (\( \exists d:D \alpha \)), sets of multi-actions can be combined using union.

¹ For more information on mCRL2 see [http://www.mcrl2.org](http://www.mcrl2.org). We used SVN revision 10606.
(∪), and complemented using negation (¬). Sets of actions can be combined into action sequences using concatenation (·) and iteration (∗).

The property b is a Boolean expression that can include data expressions that occur free as parameters to actions. The Boolean formula true holds in every state. The property [ϱ]ϕ holds if ϕ holds in all states that can be reached by a sequence conforming to ϱ. The property ⟨ϱ⟩ϕ holds if there exists such a reachable state. The greatest fixed point operator is ν. The property νX.(a)X holds in a state in which an infinite sequence of a actions is possible. Conjunction and negation of properties are as expected. For an in-depth description of the modal μ-calculus and its semantics, we refer to [GM99].

3 Session setup

The standard [IEE08] describes the communication between agents and a manager. Medical information is communicated from an agent to a manager in a reliable, asynchronous way. Various transport technologies, e.g. bluetooth, are supported.

Before any medical information, referred to as data in the rest of this paper, is transferred between the agent and the manager, both parties need to agree on a configuration. A configuration can be seen as an agreement on the meaning of the data that is transferred, e.g. the unit of weights is kilogrammes, not pounds. This configuration is established during the session setup phase of the protocol. After a configuration has been established, we say that both the agent and the manager are operating.

3.1 Modelling the session setup protocol

We first describe the initial model that we constructed based on the 2008 version of the standard, followed by our observations on this version of the standard. Session setup is specified in the standard by two UML state charts [IEE08, Figures 10 and 11], one for the agent, one for the manager. A small part of the the agent state chart is shown in Figure 2.

Multiple channels between agent and manager are supported by the standard. The systems must at least provide a primary, reliable channel. For such a channel it is assumed, among others, that messages are received in the order they are sent, and messages will not be duplicated or get lost. Session setup must take place along this primary channel, whereas all other communication is also allowed on this channel. We restrict our model to a single, primary channel between the agent and the manager modelled by two unidirectional buffers, A2M and M2A. Since we are mainly interested in the communication between agent and manager, and the correctness of the session setup protocol, we assume that all local triggers are synchronous, will be handled instantly, and require no time. A schematic view of the system we model and verify is given in Figure 1.

We systematically translate the state charts to mCRL2 using the translation from [HKL+09] to the processes Agent and Manager. We explain the translation in more detail using the state chart in Figure 2.
Example 1. Each OR-state is modelled as a sort in mCRL2’s data language. For the state chart in Figure 2, we obtain

\begin{verbatim}
sort Agent_states = struct
  | Agent_Disconnected
  | Agent_Connected
  | ...
  | Agent_nop;

Agent_Connected_states = struct
  | Agent_Connected_Disassociating
  | Agent_Connected_Unassociated
  | Agent_Connected_Associated
  | ...
  | Agent_Connected_nop;
\end{verbatim}

This declares the enumerated sort `Agent_states`, with an element for the substate `Connected`, and `Agent_Connected_states`, with one element for each of the substates of the OR-state `Connected`. The element `Agent_Connected_nop` indicates that the state `Connected` is currently inactive. The agent process gets one parameter for each OR-state, which leads to the following declaration:

\begin{verbatim}
proc Agent (Agent_state : Agent_states,
            Agent_Connected_state : Agent_Connected_states,
            ...) = ...
\end{verbatim}

This declares the process `Agent`, with parameters `Agent_state` and `Agent_Connected_state`, signifying the current state of the OR-state `Connected`. The initial state of the process is determined by the initial states in the state chart. If an OR-state is a substate of a state that is not active initially, it is assigned the corresponding `nop` value. For the example, we obtain the following initialisation.

\begin{verbatim}
init Agent (Agent_Disconnected, Agent_Connected_nop, ...);
\end{verbatim}

The signals that are communicated between the agent and the manager, and the data that is communicated have to be sent along a single communications channel. Therefore, we combine both into a single data sort `Message`.

\begin{verbatim}
sort Message = struct
  | signal (Signal)
  | data (Data);
\end{verbatim}

This sort consists of elements `signal` which carry signals as parameters, and `data` which carries elements of sort `Data` as parameters. The sort `Signal` is built from the signals that are described in the state machine, for `Data` we use an abstract data type representing measurement data, consisting of two elements.

\begin{verbatim}
sort Data = struct
  | datum1
  | datum2;

Signal = struct
  | sig_AssocAbort
  | sig_AssocRelRsp
  | sig_AssocRelReq
  | ...
\end{verbatim}

For readability of the model, we introduce functions that wrap signals into the `signal` constructor, producing a message. We write, e.g., the following, in which `AssocAbort` is a constant of sort `Message`, introduced by the keyword `map`. It is defined to be `signal(sig_AssocAbort)`, using the keyword `eqn`.

\begin{verbatim}
map AssocAbort : Message;
eqn AssocAbort = signal(sig_AssocAbort);
\end{verbatim}

Messages are transmitted along the channels using actions `send` and `receive`, which communicate into the action `communicate`. In addition, actions are declared for local triggers, e.g. `assocRelReq`.

A transition can be taken, if the process is in the state from which the transition originates in the state chart and its trigger gets enabled. For local triggers, since we assume the trigger is processed instantly and atomically, we model this using a multi-action together with the trigger. The `assocRelReq` transition in Figure 2, is e.g. modelled as follows.

\begin{verbatim}
(Agent_state == Agent_Connected
  && Agent_Connected_state == Agent_Connected_Associated) ->
  assocRelReq|send(agent_out, AssocRelReq)
  . Agent(Agent_Connected_state = Agent_Connected_Disassociating, ...)
\end{verbatim}
This says that, if the agent is connected and associated, upon triggering the local trigger assocRelReq, a signal AssocRelReq is sent immediately as defined by the +entry trigger in the Disassociating state. The state of the agent is updated according to the transition specification. In the Disassociating state, the transitions are modelled as follows.

\[
\text{(Agent\_state == Agent\_Connected } \land \text{ Agent\_Connected\_state == Agent\_Connected\_Disassociating) -> receive(agent\_in(id), AssocRelReq) . send(agent\_out(id), AssocRelRsp) . Agent(Agent\_Connected\_state = Agent\_Connected\_Unassociated) + receive(agent\_in(id), AssocRelRsp) . Agent(Agent\_Connected\_state = Agent\_Connected\_Unassociated) + ...}
\]

The + models non-deterministic choice between two alternatives. The first alternative is receiving an AssocRelReq, which triggers sending an AssocRelRsp. The second alternative is receiving an AssocRelRsp, which does not trigger an action. In both cases, the system changes state to Agent\_Connected\_Unassociated.\(^2\)

Note that the transition specifications in the state machines in [IEE08] are not complete. A full specification is given in the state transition tables in [IEE08, Annex E]. We combine the information from both sources. Although in general a single manager can serve multiple agents, for the purpose of this case study we restrict ourselves to a single agent and a single manager. This is the scenario that the standard focuses on; more specifically, the standard describes that the underlying communication layers are able to indicate that a connection between an agent and a manager has been established or aborted, hence the manager could serve each of the agents in their own context. According to the standard, both the Agent and the Manager can receive connect and disconnect indications from the transport layer at all times. We abstract from this behaviour, and assume that connect and disconnect indications are treated correctly, and we assume that always either both parties are connected, or both parties are disconnected. Upon disconnection, all messages still on the transport will be lost. This is a strong assumption on the capabilities of the transport layer, that allows us to focus on the session setup protocol.

![Fig. 2. Excerpt of the UML state machine for the Agent](image)

The overall system is constructed using parallel composition of the agent and manager process, as well as the processes A2M and M2A representing the communication channels.

**Example 2.** Sending of a message by the agent is modelled by a synchronous communication between the Agent and the A2M processes along channel agent\_out as indicated in Figure 1, likewise

\(^2\) The full model is available at [https://svn.win.tue.nl/viewvc/MCRL2/trunk/examples/industrial/ieee-11073/](https://svn.win.tue.nl/viewvc/MCRL2/trunk/examples/industrial/ieee-11073/). For convenience it is also included in the appendix.
for the other processes. This synchronisation is modelled using \textit{comm} in the initialisation. Communication is enforced using the \textit{allow} operator.

\begin{verbatim}
init allow( \{ communicate, ... \},
  comm( \{ send|receive -> communicate, ... \},
    Agent(Agent_Disconnected, Agent_Connected_nop, ...)
    || A2M([]) || M2A([])
    || Manager(Manager_Disconnected, Manager_Connected_nop, ...))));
\end{verbatim}

The standard describes the format used for configurations extensively [IEE08, Section 7.4]. In order to distinguish between different configurations, we use an abstract type for them. According to the standard, the agent provides the manager with a number of supported configurations in the association request. We do not provide these options, but assume that the agent supports all configurations of sort \textit{Configuration}, and assume that the manager can choose a configuration non-deterministically. This non-deterministic choice of a configuration models the worst-case behaviour of any manager process.

Once session setup is complete, the protocol supports different types of data transmission. The manager is allowed to get and set values, and to invoke actions supported by the agent. The agent can send configuration updates and measurement data to the manager. Since we focus on the correctness of the session setup part of the protocol, we only include the transmission of measurement data in the operating phase. Transmission of measurements can be confirmed or unconfirmed, and in our model we only use the unconfirmed version, since this is the simplest part of the protocol in the operating phase, that still allows verification of the session setup.

For verification purposes, the agent and the manager can report their configuration through an action \texttt{operating(Configuration)} once the session setup protocol has finished.

### 3.2 Observations

While modelling the 2008 version of the standard, and checking deadlock freedom of our model during the process, we observed several flaws and omissions this version of the standard. These issues were subsequently discussed with a member of the standards committee, who had access to a preliminary version of the 2010 version of the standard. Some of the issues we discovered have been fixed independently by the committee in the 2010 version of the standard. These issues have hence been discovered over the course of two years that the standard had been in use. Using our modelling approach, we have been able to find these issues in a few hours. In the rest of this section we identify the different kinds of issues that we found in the 2008 version of the standard, and indicate occurrences of these problems. In case a problem is still present in the 2010 version of the standard [IEE10] we indicate so, otherwise the problem has been resolved.

\textit{Understandability} We first discuss some general issues, that are not flaws in the the standard as such, but make the standard harder to understand. The main issue here is that the formalisms that are used throughout the standard, \textit{i.e.} UML state machines, message sequence charts and the state transition tables are not properly introduced. This means that no clear semantics can be attached to the diagrams in the standard. An example of an unclarity is the "+entry/AssocRelReq" action in the Disassociating state of the agent [IEE08, Figure 11, page 60], see also Figure 2. It turns out that the \texttt{AssocRelReq} action is performed immediately upon entering the Disassociating state.

Since there is duplication of information between the state charts and the state transition tables, it is important to understand which of the two is leading in case of an incompleteness or inconsistency. This should be clarified in the standard. Also note that the information in the state machines is incomplete. A model solely based on the state machines will lead to deadlocking behaviour.

In the rest of this section we investigate inconsistencies between different descriptions, and incompleteness of the descriptions in more detail.
**Consistency** If we take a closer look at the descriptions of the protocol in the state charts and the state transition tables, we observe several types of inconsistencies. First of all, inconsistent terminology is used to refer to the same thing in the state charts and state tables.

- The correspondence between the action names in the tables in [IEE08, Annex E], and the action names in the state charts depicted in [IEE08, Figures 10, 11] is not clear from the context. For example, the signals 2.8, 2.12 [IEE08, Table E. 2], represented by the events “aarq(*)” and “aare(*)” represent association requests and association responses respectively. These are represented in the state machines as AssocReq and AssocRsp.
- The triggers REQ agent supplied (un)supported configuration, in [IEE08, Table E. 3] (Signal ID 7.31 and 7.32) are not in the Manager state chart.

Second, the state transition tables and the state charts sometimes prescribe different state changes for the same event.

- According to the state chart [IEE08, Figure 11], the manager goes to the Unassociated state upon receiving a release request in the disassociating state, whereas according to Signal ID 9.16 in [IEE08, Table E. 3] it stays in the Disassociating state.
- The agent state chart [IEE08, Figure 10] demands that the connection is aborted immediately, whereas signal 9.16 in [IEE08, Table E. 3] mandates that the agent waits for its own release response. *This has not been fixed in the 2010 version of the standard.*
- According to [IEE08, Table E. 3], the Manager goes directly from the unassociated state to the associated state for signals with ID 2.9, 2.10 (and to Unassociated with 2.11). The state chart in [IEE08, Figure 11] contains an intermediate state Associating. After discussion it turns out that in this case the state chart is leading, and the table has been adjusted accordingly in the 2010 version of the standard.

**Completeness** The last type of problem that we identified is related to completeness. It is sometimes not specified what should happen in case an unexpected message occurs. In principle, if we follow the description of UML state machines [Obj09], such a message can be ignored. However, since for most unexpected messages the behaviour is specified in the state transition table, we expect all such situations to be described. An example of this is the Associating state of the manager, for which [IEE08, Table E. 3] does not list any transitions.

All completeness issues were discovered through the deadlock checks that we carried out on our initial model. 3 We describe the analysis in more detail in the rest of this section.

We generate the state space of the initial model, and, on the fly, check for deadlocks. For the initial model, a number of deadlocks are detected. Figure 3 shows an abstract visual representation of the state space of our initial model in the style of [vvv01]. The deadlock states are highlighted. One of the traces to a deadlock state is given in Figure 4. Inspection of this trace shows that it ends up in the situation where the Manager is in the Unassociated state, and the head of the input buffer of the Manager process is a ConfigEventReportReq message that has been sent by the Agent. The manager needs to process this message. According to the transition specification in the state machines and state tables, this message is not covered. In the rest of the standard the default procedure for treating unexpected messages is to accept the message, and respond with AssocAbort. Hence the obvious fix for these deadlocks is *to accept ConfigEventReportReq, and respond with an AssocAbort message.* Note that this message is not handled properly in a number of states, and we apply this fix in all places including the operating state.4

If we explore the fixed model, we again run into deadlocks. This time, these are caused by the Agent process, which is not willing to accept ConfigEventReportRsp messages in the Unassociated state. The fix for this issue is similar to the one above. 5 The model with the above two fixes is deadlock free.

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3 The model in the appendix behaves as the initial model if enableFix1 = enableFix2 = false.
4 This fix can be enabled by setting enableFix1 = true in the model in the appendix.
5 This fix can be enabled by setting enableFix2 = true in the model in the appendix.
Fig. 3. State space of an Agent and Manager process in 2008 version of the standard. Deadlocks are highlighted.

transport_connect
communicate(agent_out(0), AssocReq)
communicate(manager_in(1), AssocReq)
communicate(manager_out(1), AssocRsp(accepted_unknown_config))
communicate(agent_in(0), AssocRsp(accepted_unknown_config))
communicate(manager_out(1), AssocRelReq)
communicate(agent_out(0), ConfigEventReportReq)
communicate(agent_in(0), AssocRelReq)
communicate(manager_out(1), AssocAbort)

Fig. 4. Trace to a deadlock state in the model of the 2008 version of the standard.
4 Verification

In the previous section we have investigated the quality of the 2008 version of the standard. We have improved the model according to the findings. Furthermore, we updated our model to adhere to the 2010 version of the standard. The analysis we perform in the rest of this paper is based on the 2010 version of the standard, including the fixes we proposed in the previous section.

The standard does not provide any clear requirements on the session setup phase. We formulate a number of requirements, which we subsequently verify. We express all properties in the modal $\mu$-calculus, and check them on the model of the 2010 version of the standard, including the fixes from Section 3.\(^6\)

1. The system can reach a state in which the manager successfully receives data from the agent.

$$\langle true^* \rangle \exists_d.communicate(manager\_in, data(d)) \text{true}$$

2. From every state, the system can reach a state in which the manager can successfully receive data from the agent infinitely often, within a single session.

$$[true^*] \langle true^* \rangle \nu X. ((\neg \exists_{id.communicate(agent\_out, AssocReq(id)))^*})$$

$$\langle \exists_d.communicate(manager\_in, data(d)))X \rangle$$

3. When both the agent and the manager reach the operating state, then they agree on the configuration that is being used.

$$[true^*] \forall_{c,c'}[operating(c)|operating(c')](c = c')$$

4. Before measurement data is correctly communicated using the protocol, it first needs to be ensured that the agent and manager agree on the configuration that is used.

$$[true^*] \forall_{c,c'}[operating(c)|operating(c')]$$

$$[\neg \exists_{ch,m\in\{AssocAbort, AssocRelReq, AssocRelRsp\} \land communicate(ch,m))^*}]$$

$$[\exists_d.communicate(manager\_in, data(d))](c = c')$$

Requirements 1 and 2 serve as a check to see that data can be communicated as expected. Both properties hold for our model of the 2010 version of the standard. The first requirement ensures that requirement 4 does not hold trivially.

Our main focus is on requirements 3 and 4, i.e. determine whether an agent and a manager can get into an operational state with different assumptions on the data that is communicated, e.g. a state in which the agent thinks weights are transferred in kilogrammes, whereas the manager assumes weights are in pounds.

Requirement 3 is the requirement on consistent operating states as we originally formulated it. This property does not hold for the system. In fact, this is not a problem, as long as no data is successfully received by the manager in inconsistent operating states. This weaker requirement is expressed in requirement 4. We investigate both properties in detail in the rest of this section.

\(^6\) The requirements that we checked are available at https://svn.win.tue.nl/viewvc/MCRL2/trunk/examples/industrial/ieee-11073 in their concrete syntax. For convenience they are also included in the appendix.
4.1 Reachability of inconsistent operating states

If both the agent and the manager are in the operating state, they are ready to transmit measurement data. Since measurement data is interpreted according to a configuration, configurations should be consistent between the agent and the manager.

Given that the agent and the manager report their configuration if they are in the operating state, this problem can be formulated as a reachability problem. The property holds if, in all situations in which a multi-action $\text{operating}(c) | \text{operating}(c')$ can be reached, it holds that $c = c'$. If we verify this property for the system, we find that the property does not hold. A counterexample trace is shown in Figure 5. If we carefully inspect the counterexample that is produced, observe

\begin{verbatim}
transport_connect
communicate(agent_out(0), AssocReq(0))
communicate(manager_in(1), AssocReq(0))
communicate(agent_out(0), AssocAbort)
communicate(manager_out(1), AssocRsp(accepted(c1)))
communicate(manager_in(1), AssocAbort)
communicate(agent_out(0), AssocReq)
communicate(agent_in(0), AssocRsp(accepted(c1)))
communicate(manager_in(1), AssocReq)
communicate(manager_out(0), AssocRsp(accepted(c2)))
operating(c2) | operating(c1)
\end{verbatim}

Fig. 5. Trace to operating states with inconsistent configurations

that the action $\text{operating}(c2) | \text{operating}(c1)$ happens in a situation where the head of the input buffer of the manager contains an AssocReq message, and the head of the input buffer of the agent contains an AssocRsp(accepted(c2)) message. Reception of either message, will cause the sending of an AssocAbort message by the receiving party. Since on any computation path, one of these messages will be processed, before measurement data is processed, the session will always be aborted. Furthermore, measurement data is not accepted in the Unassociated state, in which both processes end up after processing the first message in each of the buffers.

Intuitively, it is clear that this concrete counterexample does not cause any safety problems. This gives rise to the weaker property that is verified in the following section.

4.2 Data shall not be transmitted in inconsistent operating states

Requirement 4 weakens requirement 3 by allowing the agent and the manager to reach inconsistent operating states, yet requiring that measurements are only successfully received by the manager if the operating states are consistent.

The structure of the formulae are similar, yet in this case, after the operating states have been reported, we allow arbitrary actions, except those that can move a system away from its operating state. Then, if the manager can successfully receive data, the configurations of the agent and the manager are required to be the same. If we verify this property using the mCRL2 toolset, we find that the property does not hold. Inspection of the model gives us the counterexample depicted in Figure 6.

The counterexample is, to a large extent, similar to the counterexample we saw previously. A session is set up, but the setup process is aborted by the agent before it has received the association response from the manager. The agent then initiates a new session setup, in which it interprets the association response from the first setup as the response corresponding to the second setup. At the point in which the $\text{operating}(c2) | \text{operating}(c1)$ actions happen, the input buffer of the manager is empty, and the input buffer of the agent contains a message AssocRsp(accepted(c1)). Since the agent is in the operating state, it can send data, as long as it does not read this message
from the buffer. Furthermore, since the manager has accepted the configuration, it is also in the operating state, hence it can accept the data the agent has sent.

transport_connect
communicate (agent_out(0), AssocReq)
communicate (manager_in(1), AssocReq)
communicate (manager_out(1), AssocRsp(accepted(c2)))
communicate (agent_out(0), AssocAbort)
communicate (manager_in(1), AssocAbort)
communicate (agent_out(0), AssocReq)
communicate (manager_in(1), AssocRsp(accepted(c2)))
communicate (manager_out(1), AssocRsp(accepted(c1)))
operating(c2) | operating(c1)
communicate (agent_out(0), data(datum1))
communicate (manager_in(1), data(datum1))

Fig. 6. Counterexample trace for requirement 4

5 Fixing the protocol

The property violations that we have seen in the previous section are caused by the mixing of AssocRsp messages across different sessions. We propose fixing this issue by adding a session identifier to the AssocReq and AssocRsp messages. Note that duplication of session identifiers is not allowed.

The changes that we make are as follows. The agent and the manager keep track of the largest session id \( t \) they have seen up to that point, initially we assume the session id is zero. In the AssocReq message, the agent includes \( t+1 \). Upon reception of this message, the manager updates her session id to the value included in this message, and includes the session id in the AssocRsp message. If the agent receives an AssocRsp message with a session id that is not equal to the session id that it stored, it will discard the response, send an AssocAbort message, and move to the unassociated state. This is similar to the treatment of other unexpected messages in the protocol.

It is crucial that session identifiers are unique and may not be repeated. In case duplicates are allowed, the agent could repeatedly send AssocReq and AssocAbort messages, until a duplicate session id is reached, and then read an old association response from the input buffer, ending up in the same problematic situation as in Figure 6. 7

The state space of the modified system is infinite. Since session identifiers need to be unique, there is no straightforward way of doing the verification in an exhaustive way. Instead we verify a version of the model in which we count session identifiers modulo some maximum value maxSessionId, and, once the first session identifier is reused we clear the buffers. Basically, this resembles the fairness assumption that, once the agent has attempted maxSessionId session setups, it has also read M messages from its input buffer, where M is buffer size. For this version of the model we are able to verify that all properties hold. Given the correct behaviour of the protocol in the case with periodic session identifiers and fairness assumptions, we argue that it is reasonable to assume that the protocol is also safe in the case without fairness assumptions if session identifiers are never reused.

7 The model in the appendix uses session ids if enableSessionIds = true
6 Conclusions

In this paper we investigated the IEEE-10073-20601 standard for personal health devices. An analysis of the 2008 version of the standard uncovered several omissions and inconsistencies. The omissions in the standard introduce deadlocks in the system, but these can easily be fixed. Most of the issues uncovered have been fixed in the 2010 version of the standard. One issue remains unfixed.

A further analysis of the 2010 version of the standard, including a fix for the remaining problem, revealed that agents and manager can reach inconsistent operating states. This is problematic, since measurement data can be transferred from the agent to the manager, and be interpreted incorrectly by the manager. Use of the incorrectly interpreted measurement data poses a serious health hazard.

We fixed the protocol by introducing a session identifier, and verified that the fixed version of the protocol satisfies the requirements. Given the bugs we detected, we recommend the full verification of the rest of standard.

The case study performed in this paper demonstrates once more that formal modelling is an invaluable addition to the standardisation process. It helps to remove ambiguities, and enables detection of inconsistencies and omissions in the standard in a short period of time. A formal model opens up the way to verification of the protocol that is described. However, in order to perform verification, a clear formulation of the requirements is indispensable. Unfortunately, these requirements are often not described within standards. Our case study shows that unverified standards can contain subtle, hard to find errors. It is our conviction that any unverified communication scheme is likely to contain bugs.

We are convinced that, without formal verification, subtle bugs end up in devices. Often, these bugs cannot be fixed without breaking conformance to the standard. Formal verification allows the early detection of these issues. Therefore, we are lead to believe that formal verification should be considered as part of the development process of a communication standard.

Acknowledgements We are grateful to an anonymous member of the standards committee, for his support and fruitful collaboration in this preliminary analysis. Furthermore, we would like to thank Erik de Vink and Tim Willemse for their helpful comments on an earlier version of this paper.

References

In this section we list the requirements that were used in their concrete syntax.

1. The system can reach a state in which the manager successfully receives data from the agent.

\[
\begin{align*}
\text{true} & \quad \exists d : \text{Data} . \text{communicate}(\text{manager\_in}(1), \text{data}(d))
\end{align*}
\]

2. From every state, the system can reach a state in which the manager can successfully receive data from the agent infinitely often, within a single session.

\[
\begin{align*}
\text{true} & \quad \nu X . \\
\exists ! (\exists id : \text{SessionId} . \text{val}(id < maxSessionId) \\
& \quad \& \text{communicate}(\text{agent\_out}(0), \text{AssocReq}(id))) & \\
\exists d : \text{Data} . \text{communicate}(\text{manager\_in}(1), \text{data}(d)) & X
\end{align*}
\]

3. When both the agent and the manager reach the operating state, then they agree on the configuration that is being used.

\[
\begin{align*}
\text{true} & \quad \forall c, c' : \text{Configuration} . \\
\text{operating}(c) & \land \text{operating}(c') & (\text{val}(c == c'))
\end{align*}
\]

4. Before measurement data is correctly communicated using the protocol, it first needs to be ensured that the agent and manager agree on the configuration that is used.

\[
\begin{align*}
\text{true} & \quad \forall c, c' : \text{Configuration} . \\
\text{operating}(c) & \land \text{operating}(c') & \exists ! (\exists ch : \text{ChannelId} . \\
& \quad \text{communicate}(ch, \text{AssocAbort}) \\
& \quad \lor \text{communicate}(ch, \text{AssocRelReq}) \\
& \quad \lor \text{communicate}(ch, \text{AssocRelRsp}))) & \\
\exists d : \text{Data} . \text{communicate}(\text{manager\_in}(1), \text{data}(d)) & (\text{val}(c == c'))
\end{align*}
\]
B Model

Model of session setup of IEEE 11073-20601
based on IEEE 11073-20601-2008, augmented with information from the ratified
version of 2010.

This model was analysed in J.J.A. Keiren and M. D. Klabbers, "Modelling and
verifying the IEEE Std 11073-20601 session setup using mCRL2".

Model by Jeroen Keiren
Last change: 5 June 2012

The configuration has two parameters that change the behaviour, see the
accompanying report for more information.

* enableFix1: fix deadlocks in the specification by allowing the Manager
to receive ConfigEventReportReq in situations where this is not
expected.
* enableFix2: fix deadlocks in the specification by allowing the Agent to
receive ConfigEventReportRsp in situations where this is not
expected.
* enableSessionIds: Fix the protocol by introducing session ids.
* wrapSessionIds: Make the model finite by counting session ids modulo
maxSessionId + 1.
* clearBuffersOnWrap: If maxSessionId session ids have been used, and a new
session id is needed, clear the buffers if wrapSessionIds is
enabled. This models the fairness assumption that before
maxSessionId + 1 session ids have been used, a message has been
read from both buffers at least M times.

Notes on the specification:
* Numbers in comments in processes indicate Signal IDs in the transition
tables of the IEEE standard.
* (revised) indicates that the rule corresponds to the rule in the 2010
ratified version of the standard, rather that the 2008 version.

System sketch

<table>
<thead>
<tr>
<th>-----</th>
<th>Agent</th>
<th>-----</th>
<th>Manager</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0)</td>
<td>Agent</td>
<td>(1)</td>
<td></td>
</tr>
<tr>
<td>(0)</td>
<td></td>
<td>(1)</td>
<td></td>
</tr>
</tbody>
</table>

Model parameters, can be used to toggle several versions of the model.

map enableFix1, enableFix2, enableSessionIds, wrapSessionIds, clearBuffersOnWrap: Bool;
eqn

% enableFix1: if set to true, ConfigEventReportReq messages are handled by
% the manager in every state, if false, this message is treated as in the
% 2008 version of the standard.
% enableFix1 = true;

% enableFix2: if set to true, ConfigEventReportRsp messages are handled by
% the agent in every state, if false, this message is treated as in the
% 2008 version of the standard.
% enableFix2 = true;

% enableSessionIds: if set to true, add session ids to the AssocReq and
% AssocRsp messages. This fixes correctness of the protocol.
% enableSessionIds = true;

% wrapSessionIds: if set to true, count session ids modulo maxSessionId,
% otherwise increment, leading to an infinite state space.
% wrapSessionIds = true;

% clearBuffersOnWrap: if set to true, the buffers are emptied once the
% session id is wrapped, otherwise the buffers are unchanged
% clearBuffersOnWrap = true;

% Max buffer size
map M: Nat;
eqn M = 1;
% The maximum session id that should be used.
% Only relevant if enableSessionIds is set.
map maxSessionId : Nat;
eqn maxSessionId = 1;

% Process identifier (for introducing multiple agents/managers)
sort Id = Nat;

% SessionIds to session ids.
sort SessionId = Nat;
map session0 : Nat;
eqn session0 = 0;

% Compute the next session id.
map next : Nat -> Nat;
var n : Nat;
eqn
  % Count modulo maxSessionId + 1, if we use session ids, and want to wrap.
  (enableSessionIds && wrapSessionIds) -> next(n) = (n+1) mod Nat2Pos(maxSessionId+1);
  % Just increment if we use session ids, and do not want to wrap.
  (enableSessionIds && ! wrapSessionIds) -> next(n) = n+1;
  % Add the same session id to every message, in case we do not want to use session ids.
  ! enableSessionIds -> next(n) = n;

% Communication channels
sort ChannelId = struct agent_in (Id)
  | agent_out (Id)
  | manager_in (Id)
  | manager_out (Id);

% Message content for association response
sort AssociationResponse = struct rejected
  | accepted(Configuration)
  | accepted_unknown_config;

% Message content for configuration response
sort ConfigEventReportResponse = struct accepted_config(Configuration)
  | unsupported_config;

% Dummy configurations, used for showing differences in configurations
sort Configuration = struct c1 | c2;

% Abstract type for data; abstracts from concrete messages that can be sent in the operating state.
sort Data = struct datum1;

% Signals that can be sent in the system
sort Signal = struct sig_AssocReq(SessionId)
  | sig_AssocRelReq
  | sig_AssocAbort
  | sig_AssocRelRsp
  | sig_AssocAbortReq
  | sig_AssocAbortRsp
  | sig_AssocAbortReq
  | sig_ConfigEventReportReq
  | sig_ConfigEventReportRsp(ConfigEventReportResponse);

% Generic message type, to allow sending Data and Signals along the same channel
sort Message = struct signal(Signal) | data(Data);

% Embed the signals as described in the standard/the paper into the message data type.
map AssocReq : SessionId -> Message;
  AssocRelReq ,
  AssocAbort ,
  AssocRelRsp : Message;
  AssocRsp : SessionId # AssociationResponse -> Message;
  ConfigEventReportReq : Message;
var t : SessionId;
ar : AssociationResponse;
cr : ConfigEventReportResponse;
c : Configuration;
eqn AssocReq(t) = signal(sig_AssocReq(t));
AssocRelReq = signal(sig_AssocRelReq);
AssocAbort = signal(sig_AssocAbort);
AssocRelRsp = signal(sig_AssocRelRsp);
AssocRsp(t, ar) = signal(sig_AssocRsp(t, ar));
ConfigEventReportReq = signal(sig_ConfigEventReportReq);
ConfigEventReportRsp(cr) = signal(sig_ConfigEventReportRsp(cr));
% Actions for communicating along the above mentioned channels
act send, receive, communicate: ChannelId # Message;

% Actions local for the Agent/Manager
act assocReq;
assocAbortReq;
sendConfigReportReq;
LookupConfig;
agentSuppliedUnsupportedConfigReq;
agentSuppliedSupportedConfigReq;

% Actions for synchronous connect and disconnect of transport
act transport_connect_agent;
transport_connect_manager;
transport_connect_notify;
transport_connect;
clear;
reset_buffers;
Reset_Buffers;
transport_disconnect_agent;
transport_disconnect_manager;
transport_disconnect_notify;
transport_disconnect;

act operating: Configuration; % Report the configuration in the operating state

% Or states of the state chart
sort Agent_states =
struct Agent_Disconnected
| Agent_Connected
| Agent_nop;

sort Agent_Connected_states =
struct Agent_Connected_Disassociating
| Agent_Connected_Unassociated
| Agent_Connected_Associating
| Agent_Connected_Associated
| Agent_Connected_nop;

sort Agent_Connected_Associated_states =
struct Agent_Connected_Associated_Operating(Configuration)
| Agent_Connected_Associated_Configuring
| Agent_Connected_Associated_nop;

sort Agent_Connected_Associated_Configuring_states =
struct Agent_Connected_Associated_Configuring_WaitingApproval
| Agent_Connected_Associated_Configuring_SendingConfig
| Agent_Connected_Associated_Configuring_nop;

% Agent process
proc Agent(id: Id, t: SessionId,
Agent_state: Agent_states,
Agent_Connected_state: Agent_Connected_states,
Agent_Connected_Associated_state: Agent_Connected_Associated_states,
Agent_Connected_Associated_Configuring_state:
Agent_Connected_Associated_Configuring_states) =

% Disconnected
(Agent_state == Agent_Disconnected) ->
{
    % 1, 2, 3, 4, 5, 2, 8, 1, 9
    transport_connect_agent;
    Agent(Agent_state = Agent_Disconnected,
    Agent_Connected_state = Agent_Connected_Unassociated)
}

% Connected
+ (Agent_state == Agent_Connected) ->
{
    % 2, 3
    transport_disconnect_agent;
    Agent(Agent_state = Agent_Disconnected,
    Agent_Connected_state = Agent_Connected_nop,
    Agent_Connected_Associated_state = Agent_Connected_Associated_nop,
    Agent_Connected_Associated_Configuring_state =
    Agent_Connected_Associated_Configuring_nop)
}
= Agent_Connected_Associated_Configuring_msg)

%%% Connected - Disassociating
+ (Agent_state == Agent_Connected
 && Agent_Connected_state == Agent_Connected_Disassociating) ->
  ( assocRelReq | Agent() 9.6
  + assocAbortReq | send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated) 9.7
  + sum t': SessionId
  . receive(agent_in(id), AssocReq(t'))
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated) 9.8
  + sum r: AssociationResponse , t': SessionId
  . receive(agent_in(id), AssocRsp(t', r))
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated) 9.12
  + receive(agent_in(id), AssocRelReq)
  . send(agent_out(id), AssocRelRsp)
  . Agent() 9.16;
  % state chart says:
  % Agent(Agent_Connected_state == Agent_Connected_Unassociated)
  + receive(agent_in(id), AssocRelRsp)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated) 9.17
  + receive(agent_in(id), AssocAbort)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated) 9.18
  + (enableFix2 -> sum r: ConfigEventReportResponse
  receive(agent_in(id), ConfigEventReportRsp(r))
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated))

%Ignore 9.21
%Ignore 9.26

%%% Connected - Unassociated
+ (Agent_state == Agent_Connected
 && Agent_Connected_state == Agent_Connected_Unassociated) ->
  ( (t == maxSessionId && clearBuffersOnWrap) -> reset_buffers
  . assocReq | send(agent_out(id), AssocReq(next(t)))
  . Agent(Agent_Connected_state == Agent_Connected_Associating ,
  t = next(t)) 2.5
  <> assocReq | send(agent_out(id), AssocReq(next(t))) 2.5
  + assocRelReq
  . Agent() 2.6
  + assocAbortReq
  . Agent() 2.7 Should not happen
  + sum t': SessionId
  . receive(agent_in(id), AssocReq(t'))
  . send(agent_out(id), AssocRsp(t', rejected))
  . Agent() 2.8 Agent-agent association
  + sum r: AssociationResponse , t': SessionId
  . receive(agent_in(id), AssocRsp(t', r))
  . send(agent_out(id), AssocAbort)
  . Agent() 2.18 Should not happen
  + receive(agent_in(id), AssocRelReq)
  . send(agent_out(id), AssocRelRsp)
  . Agent() 2.19 Should not happen
  + receive(agent_in(id), AssocAbort)
  . Agent() 2.17 Should not happen. Ignore
  + receive(agent_in(id), AssocAbort)
  . Agent() 2.18
  + (enableFix2 -> sum r: ConfigEventReportResponse
  receive(agent_in(id), ConfigEventReportRsp(r))
  . send(agent_out(id), AssocAbort)
  . Agent())

%Ignore 2.19 Should not happen

%%% Connected - Associating
+ (Agent_state == Agent_Connected
 && Agent_Connected_state == Agent_Connected_Associating) ->
  ( %Ignore 3.3 Timeout, retry
  %Ignore 3.4 Timeout, abort
  assocRelReq | send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated) 3.6
  + assocAbortReq | send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state == Agent_Connected_Unassociated) 3.7
+ sum t: SessionId
  receive(agent_in(id), AssocReq(t'))
  . send(agent_out(id), AssocReq(t', rejected))
  . Agent() % 3.8
+ sum c: Configuration, t: SessionId
  receive(agent_in(id), AssocRsp(t', accepted(c)))
  (t == t') -> Agent(Agent_Connected_state = Agent_Connected_Associated,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_Operating(c)) % 3.13
  <> send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated)
+ sum t: SessionId
  receive(agent_in(id), AssocRsp(t', accepted_unknown_config))
  (t == t') -> Agent(Agent_Connected_state = Agent_Connected_Associated,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_Configuring,
    Agent_Connected_Associated_Configuring_state
    = Agent_Connected_Associated_Configuring_SendingConfig) % 3.14
  <> send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated)
+ sum t: SessionId
  receive(agent_in(id), AssocRsp(t', rejected))
  (t == t') -> Agent(Agent_Connected_state = Agent_Connected_Unassociated) % 3.15
  <> send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated)
+ receive(agent_in(id), AssocRelReq)
  . send(agent_out(id), AssocRelRsp)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated)
    % 3.16 Should not happen
+ receive(agent_in(id), AssocRelRsp)
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated)
    % 3.17 Should not happen
+ sum r: AssociationResponse, t: SessionId
  receive(agent_in(id), AssocRsp(t', r))
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_nop,
    Agent_Connected_Associated_Configuring_state
    = Agent_Connected_Associated_Configuring_nop,
    Agent_Connected_Associated_ConfiguringSendingConfig
    = Agent_Connected_Associated_Configuring_SendingConfig)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated)
+ (enableFix2 -> sum r: ConfigEventReportResponse
  receive(agent_in(id), ConfigEventReportRsp(r))
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated))

% Ignore 3.19 Should not happen

XXXX Connected - Associated
+ (Agent_state == Agent_Connected
  && Agent_Connected_state == Agent_Connected_Associated) ->
  (assocRelReq|send(agent_out(id), AssocRelReq)
  . Agent(Agent_Connected_state = Agent_Connected_Disassociating,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_nop,
    Agent_Connected_Associated_Configuring_state
    = Agent_Connected_Associated_Configuring_nop) % 4.6, 5.6, 8.6
+ assocAbortReq|send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_nop,
    Agent_Connected_Associated_Configuring_state
    = Agent_Connected_Associated_Configuring_nop) % 4.7, 5.7, 8.7
+ sum t: SessionId
  receive(agent_in(id), AssocReq(t'))
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_nop,
    Agent_Connected_Associated_Configuring_state
    = Agent_Connected_Associated_Configuring_nop) % 4.8, 5.8, 8.8
+ sum r: AssociationResponse, t: SessionId
  receive(agent_in(id), AssocRsp(t', r))
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_nop,
    Agent_Connected_Associated_Configuring_state
    = Agent_Connected_Associated_Configuring_nop) % 4.12, 5.12, 8.12
+ receive(agent_in(id), AssocRelReq)
  . send(agent_out(id), AssocRelRsp)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated,
    Agent_Connected_Associated_state
    = Agent_Connected_Associated_nop,
    Agent_Connected_Associated_Configuring_state
    = Agent_Connected_Associated_Configuring_nop) % 4.16, 5.16, 8.16
+ receive(agent_in(id), AssocRelRsp)
  . send(agent_out(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated, Agent_Connected_Associated_state = Agent_Connected_Associated_nop, Agent_Connected_Associated_Configuring_state = Agent_Connected_Associated_Configuring_nop) % 4.17, 5.17, 8.17
+ receive(agent_in(id), AssocAbort)
  . Agent(Agent_Connected_state = Agent_Connected_Unassociated, Agent_Connected_Associated_state = Agent_Connected_Associated_nop, Agent_Connected_Associated_Configuring_state = Agent_Connected_Associated_Configuring_nop) % 4.18, 5.18, 8.18

% %%% Connected - Associated - Operating
% When operating, responses from the configuring phase need to be handled appropriately.
+ sum c: Configuration
  . (Agent_state == Agent_Connected
  && Agent_Connected_state == Agent_Connected_Associated
  && Agent_Connected_Associated_state == Agent_Connected_Associated_Operating(c)) ->
    (operating(c)
     . Agent()
     + sum d: Data . send(agent_out(id), data(d))
     . Agent()
     + (enableFix2 -> sum r: ConfigEventReportResponse
        receive(agent_in(id), ConfigEventReportRsp(r))
        . send(agent_out(id), AssocAbort)
        . Agent(Agent_Connected_state = Agent_Connected_Unassociated, Agent_Connected_Associated_state = Agent_Connected_Associated_nop, Agent_Connected_Associated_Configuring_state = Agent_Connected_Associated_Configuring_nop))

% Ignore 8.21
% Ignore 8.26
% %%% Connected - Associated - Configuring
% NOP
% %%% Connected - Associated - Configuring - Waiting Approval
+ (Agent_state == Agent_Connected
  && Agent_Connected_state == Agent_Connected_Associated
  && Agent_Connected_Associated_state == Agent_Connected_Associated_Configuring
  && Agent_Connected_Associated_Configuring_state == Agent_Connected_Associated_Configuring_WaitingApproval) ->
  (Ignore 5.22
  Ignore 5.23
  receive(agent_in(id), ConfigEventReportRsp(unsupported_config))
  . Agent(Agent_Connected_Associated_Configuring_state = Agent_Connected_Associated_Configuring_SendingConfig) % 5.27
  + sum c: Configuration
  . receive(agent_in(id), ConfigEventReportRsp(accepted_config(c)))
  . Agent(Agent_Connected_Associated_state = Agent_Connected_Associated_Operating(c),
          Agent_Connected_Associated_Configuring_state = Agent_Connected_Associated_Configuring_nop) % 5.29
% Ignore 5.30
% %%% Connected - Associated - Configuring - Sending Config
+ (Agent_state == Agent_Connected
  && Agent_Connected_state == Agent_Connected_Associated
  && Agent_Connected_Associated_state == Agent_Connected_Associated_Configuring
  && Agent_Connected_Associated_Configuring_state == Agent_Connected_Associated_Configuring_SendingConfig) ->
  (Ignore 4.22
  Ignore 4.23
  Ignore 4.26
  sendConfigReportReq | send(agent_out(id), ConfigEventReportReq)
  . Agent(Agent_Connected_Associated_Configuring_state = Agent_Connected_Associated_Configuring_WaitingApproval) % 4.32
  + (enableFix2 -> sum r: ConfigEventReportResponse
     . receive(agent_in(id), ConfigEventReportRsp(r))
     . send(agent_out(id), AssocAbort)
     . Agent(Agent_Connected_state = Agent_Connected_Unassociated, Agent_Connected_Associated_state = Agent_Connected_Associated_nop, Agent_Connected_Associated_Configuring_state = Agent_Connected_Associated_Configuring_nop) % 4.33
  )
\begin{verbatim}
= Agent_Connected_Associated_nop,
Agent_Connected_Associated_Configuring_state
= Agent_Connected_Associated_Configuring_nop)

;

\end{verbatim}
+ receive(manager_in(id), AssocRelReq).
  . send(manager_out(id), AssocRelRsp).
  . Manager() % 9.16
+ receive(manager_in(id), AssocRelRsp).
  . Manager(Manager_Connected_state = Manager_Connected_Unassociated) % 9.17
+ receive(manager_in(id), AssocAbort).
  . Manager(Manager_Connected_state = Manager_Connected_Unassociated) % 9.18
+ (enableFix1 -> receive(manager_in(id), ConfigEventReportReq).
  . send(manager_out(id), AssocAbort).
  . Manager(Manager_Connected_state = Manager_Connected_Unassociated))
+ sum d: Data
  . receive(manager_in(id), data(d))
  . send(manager_out(id), AssocAbort).
  . Manager(Manager_Connected_state = Manager_Connected_Unassociated)

%Ignore 9.21
%Ignore 9.26

%%% Connected - Unassociated
+ (Manager_state == Manager_Connected
  && Manager_Connected_state == Manager_Connected_Unassociated) ->
  ( AssocRelReq
    . Manager() % 2.6 Should not happen. Ignore.
  + AssocAbortReq
  . send(manager_out(id), AssocAbort).
  . Manager() % 2.7 Should not happen. Ignore. (revised send AssocAbort)
  + sum t': SessionId
  . receive(manager_in(id), AssocReq(t'))
  . Manager(Manager_Connected_state = Manager_Connected_Associating,
    t = t')
  % 2.8 (revised)
  + sum r: AssociationResponse, t': SessionId
  . receive(manager_in(id), AssocResp(t', r))
  . send(manager_out(id), AssocAbort).
  . Manager() % 2.12 Should not happen
  + receive(manager_in(id), AssocAbort).
  . send(manager_out(id), AssocAbort).
  . Manager() % 2.16 Should not happen
  + receive(manager_in(id), AssocAbort).
  . Manager() % 2.17 Should not happen. Ignore
  + receive(manager_in(id), AssocAbort).
  . Manager() % 2.18 Should not happen. Ignore
  + (enableFix1 -> receive(manager_in(id), ConfigEventReportReq).
  . send(manager_out(id), AssocAbort).
  . Manager())
  + sum d: Data
  . receive(manager_in(id), data(d))
  . send(manager_out(id), AssocAbort).
  . Manager()

%Ignore 2.19

%%% Connected - Associating
+ (Manager_state == Manager_Connected
  && Manager_Connected_state == Manager_Connected_Associating) ->
  ( AssocRelReq|send(manager_out(id), AssocAbort)
    . Manager(Manager_Connected_state = Manager_Connected_Unassociated) % 3.6 (revised)
  + AssocAbortReq|send(manager_out(id), AssocAbort)
    . Manager(Manager_Connected_state = Manager_Connected_Unassociated) % 3.7 (revised)
  + sum t': SessionId
  . receive(manager_in(id), AssocReq(t'))
  . send(manager_out(id), AssocAbort).
  . Manager(Manager_Connected_state = Manager_Connected_Associating)
  % 3.8 (revised) Should not happen
  + sum r: AssociationResponse, t': SessionId
  . receive(manager_in(id), AssocResp(t', r))
  . send(manager_out(id), AssocAbort)
  . Manager(Manager_Connected_state = Manager_Connected_Associating)
  % 3.12 (revised) Should not happen
  + receive(manager_in(id), AssocAbort).
  . send(manager_out(id), AssocAbort).
  . Manager(Manager_Connected_state = Manager_Connected_Associating)
  % 3.16 (revised)
  + receive(manager_in(id), AssocRelRsp)
  . send(manager_out(id), AssocAbort).
  . Manager() % 3.17 (revised)
  + receive(manager_in(id), AssocAbort).
  . send(manager_out(id), AssocAbort).
  . Manager(Manager_Connected_state = Manager_Connected_Unassociated)
% 3.10 (revised)
+ LookupConfig | send(manager_out(id), AssocRsp(t, rejected))
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated)

% 3.11 (revised)
+ sum c: Configuration
  + LookupConfig | send(manager_out(id), AssocRsp(t, accepted(c)))
  . Manager (Manager_Connected_state = Manager_Connected_Associated, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_Operating(c))
+ LookupConfig | send(manager_out(id), AssocRsp(t, acceptedunknown_config))
  . Manager (Manager_Connected_state = Manager_Connected_Associated, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_Configuring, 
    Manager_Connected_Associated_Configuring_state = Manager_Connected_Associated_Configuring_WaitingForConfig)

% 3.9 (revised)
+ (enableFix1 -> receive(manager_in(id), ConfigEventReportReq) 
  . send(manager_out(id), AssocAbort) 
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated))
+ sum d: Data
  . receive(manager_in(id), data(d))
  . send(manager_out(id), AssocAbort)
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated)

%%% Connected - Associated
+ (Manager_state == Manager_Connected 
  && Manager_Connected_state == Manager_Connected_Associated) -> 
( 
%Ignore 6.4, 7.4, 8.4 timeout, abort
  assocRelReq | send(manager_out(id), AssocRelReq) 
  . Manager (Manager_Connected_state = Manager_Connected_Disassociating, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_nop, 
    Manager_Connected_Associated_Configuring_state = Manager_Connected_Associated_Configuring_nop) % 6.6, 7.6, 8.6
+ assocAbortReq | send(manager_out(id), AssocAbort) 
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_nop, 
    Manager_Connected_Associated_Configuring_state = Manager_Connected_Associated_Configuring_nop) % 6.7, 7.7, 8.7
+ sum t’: SessionId
  . receive(manager_in(id), AssocReq(t’))
  . send(manager_out(id), AssocAbort) 
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_nop, 
    Manager_Connected_Associated_Configuring_state = Manager_Connected_Associated_Configuring_nop) % 6.12, 7.12, 8.12 Should not happen
+ receive(manager_in(id), AssocRelReq) 
  . send(manager_out(id), AssocRelRsp)
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_nop, 
    Manager_Connected_Associated_Configuring_state = Manager_Connected_Associated_Configuring_nop) % 6.16, 7.16, 8.16
+ receive(manager_in(id), AssocRelRsp)
  . send(manager_out(id), AssocAbort) 
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_nop, 
    Manager_Connected_Associated_Configuring_state = Manager_Connected_Associated_Configuring_nop) % 6.17, 7.17, 8.17 Should not happen
+ receive(manager_in(id), AssocAbort) 
  . Manager (Manager_Connected_state = Manager_Connected_Unassociated, 
    Manager_Connected_Associated_state = Manager_Connected_Associated_nop, 
    Manager_Connected_Associated_Configuring_state = Manager_Connected_Associated_Configuring_nop)
% Connected - Associated - Operating
% When operating, responses from the configuring phase need to be handled
% appropriately.
+ sum c: Configuration
  . (Manager_state == Manager_Connected
   && Manager_Connected_state == Manager_Connected_Associated
   && Manager_Connected_Associated_state
   == Manager_Connected_Associated_Operating(c)) ->
    (operating(c)
     . Manager()
     + sum d: Data . receive(manager_in(id), data(d))
     . Manager()
     + (enableFix1 -> receive(manager_in(id), ConfigEventReportReq)
      . send(manager_out(id), AssocAbort)
      . Manager(Manager_Connected_state = Manager_Connected_Associated, Manager_Connected_Associated_state
      = Manager_Connected_Associated_nop, Manager_Connected_Associated_Configuring_state
      = Manager_Connected_Associated_Configuring_nop))
  )

% Connected - Associated - Configuring
% No common operations

% Connected - Associated - Configuring - Checking Config
+ (Manager_state == Manager_Connected
 && Manager_Connected_state == Manager_Connected_Associated
 && Manager_Connected_Associated_state
 == Manager_Connected_Associated_Configuring
 && Manager_Connected_Associated_Configuring_state
 == Manager_Connected_Associated_Configuring_CheckingConfig) ->
  (receive(manager_in(id), ConfigEventReportReq)
   . Manager(Manager_Connected_Associated_Configuring_state
   = Manager_Connected_Associated_Configuring_WaitingForConfig)
   + sum c: Configuration
   . agentSuppliedUnsupportedConfigReq | send(manager_out(id), ConfigEventReportRsp(unsupported_config))
   . Manager(Manager_Connected_Associated_Configuring_state
   = Manager_Connected_Associated_Configuring_WaitingForConfig, Manager_Connected_Associated_state
   = Manager_Connected_Associated_nop, Manager_Connected_Associated_Configuring_state
   = Manager_Connected_Associated_Configuring_nop, Manager_Connected_Associated_Configuring_nop)
   + sum d: Data
   . receive(manager_in(id), ConfigEventReportReq)
   . send(manager_out(id), AssocAbort)
   . Manager(Manager_Connected_state = Manager_Connected_Associated, Manager_Connected_Associated_state
   = Manager_Connected_Associated_nop, Manager_Connected_Associated_Configuring_state
   = Manager_Connected_Associated_Configuring_nop))

% Connected - Associated - Configuring - Waiting for Config
+ (Manager_state == Manager_Connected
 && Manager_Connected_state == Manager_Connected_Associated
 && Manager_Connected_Associated_state
 == Manager_Connected_Associated_Configuring
 && Manager_Connected_Associated_Configuring_state
 == Manager_Connected_Associated_Configuring_WaitingForConfig) ->
  (receive(manager_in(id), ConfigEventReportReq)
   . Manager(Manager_Connected_Associated_Configuring_state
   = Manager_Connected_Associated_Configuring_WaitingForConfig) % 6.24
   + sum d: Data

%
receive (manager_in(id), data(d))
send (manager_out(id), AssocAbort)
Manager (Manager_Connected_state = Manager_Connected_Unassociated,
Manager_Connected_Associated_state
= Manager_Connected_Associated_nop,
Manager_Connected_Associated_Configuring_state
= Manager_Connected_Associated_Configuring_nop)

% Ignore 6.25
% Ignore 6.26

Buffers for asynchronous communication

Buffer connects to two communication channels

% Internally, the buffer contents is stored as a list.
proc Buffer (channel_in: ChannelId, channel_out: ChannelId, buf: List(Message)) =
  sum m: Message
  . (#buf < M)
  -> receive (channel_in, m)
  . Buffer (channel_in, channel_out, buf <| m)
  + (buf != [])
  -> send (channel_out, head (buf))
  . Buffer (channel_in, channel_out, tail (buf))
  + clear
  . Buffer (channel_in, channel_out, [])
  + reset_buffers
  . Buffer (channel_in, channel_out, []);

proc A2M (aid: Id, mid: Id, buf: List(Message)) = Buffer (agent_out(aid), manager_in(mid), buf);
proc M2A (mid: Id, aid: Id, buf: List(Message)) = Buffer (manager_out(mid), agent_in(aid), buf);

System

init
hide(
  { assocReq,
    assocAbortReq,
    assocRelReq,
    sendConfigReportReq,
    LookupConfig,
    agentSuppliedUnsupportedConfigReq,
    agentSuppliedSupportedConfigReq }
),
allow(
  { communicate,
    transport_connect,
    transport_disconnect,
    operating,
    operating|operating,
    ResetBuffers,
    communicate|assocReq,
    communicate|assocAbortReq,
    communicate|assocRelReq,
    communicate|sendConfigReportReq,
    communicate|LookupConfig,
    communicate|agentSuppliedUnsupportedConfigReq,
    communicate|agentSuppliedSupportedConfigReq }
),
comm(
  { send|receive -> communicate,
    transport_connect_agent|transport_connect_manager -> transport_connect,
    transport_disconnect_agent|transport_disconnect_manager,
    clear|clear -> transport_disconnect,
    reset_buffers|reset_buffers|reset_buffers -> ResetBuffers }
),
Agent(0, session0,
Agent_Disconnected,
Agent_Connected_nop,
Agent_Connected_Associated_nop,
Agent_Connected_Associated_Configuring_nop)
|| A2M(0, 1, [])
|| M2A(1, 0, [])
|| Manager(1, session0,
  Manager_Disconnected,
  Manager_Connected_nop,
  Manager_Connected_Associated_nop,
  Manager_Connected_Associated_Configuring_nop)
);
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