Formal verification of unreliable failure detectors in partially synchronous systems

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Formal Verification of Unreliable Failure Detectors in Partially Synchronous Systems

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Abstract. In this paper, we formally verify four algorithms proposed in [M. Larrea, S. Arévalo and A. Fernández, Efficient Algorithms to Implement Unreliable Failure Detectors in Partially Synchronous Systems, 1999]. Each algorithm is specified formally as a network of timed automata and is verified with respect to completeness and accuracy properties. Using the model-checking tool UPPAAL, we detect and report the occurrences of deadlock (for all algorithms) between each pair of non-faulty nodes due to buffer overflow in communication channels with arbitrarily large buffers. We propose one solution for deadlock avoidance. Moreover, we use one of the algorithms studied in this paper as a measure to compare the effectiveness of three model-checking tools, namely, UPPAAL, mCRL2 and FDR2. We also show that all algorithms satisfy their completeness and accuracy properties if the required number of processes remain operational.

1 Introduction

Distributed systems are vulnerable to faults such as a crash of the participating processes or the communication media among them. A key challenge is to design distributed failure detectors that allow processes to distinguish slow processes from those which have crashed. It is important that these detectors are accurate, i.e., do not suspect correct processes, and complete, i.e., do suspect crashed ones. Given their non-trivial design, it is highly desirable to validate that these protocols satisfy their required or claimed properties. M. Larrea et al. introduce “efficient algorithms to implement failure detectors in partially synchronous systems” in [10], whose formal verification forms the subject matter of this paper.

1.1 Types of unreliable failure detectors

A failure detector is called unreliable, if it can mistakenly report a correct process (a process that remains operational during the protocol) as faulty (also known as suspected or crashed). Chandra and Toueg proposed unreliable failure detectors in [3] to guarantee two essential properties, namely, completeness and accuracy. Completeness is about suspecting each faulty process and accuracy concerns not suspecting any correct process. These properties are further classified into weak and strong as follows:

1. **Strong completeness**: Eventually every faulty process is permanently suspected by *every* non-faulty process.
2. **Weak completeness**: Eventually every faulty process is permanently suspected by *some* non-faulty process.
3. **Eventual strong accuracy**: Eventually no correct process is suspected by any correct process.
4. **Eventual weak accuracy**: Eventually *some* correct process is not suspected by any correct process.
1.2 Partial synchrony

In distributed systems upper bounds on message delivery times (across communication channels) and message processing times play an important role in fault detection. For example, it is impossible to distinguish a slow process from a faulty one when there are no such upper bounds on the times activities table, i.e., in a totally asynchronous system [4]. In [3], a system is designated as partially synchronous, if there exist upper bounds for message delivery; such upper bounds are assumed to be unknown and hold only after an unknown stabilization interval. It is assumed that after the stabilization interval, every sent message is eventually received within the upper bound on the channel and process delays, provided that their communication channel is up and both the sender and the receiver are also correct. The protocols described in [10] and analyzed here are supposed to guarantee their properties only in the partially synchronous setting.

1.3 Introduction to UPPAAL

UPPAAL is a toolbox used for modeling and verification of real time distributed systems [11]. Behaviour of a process is defined as a finite state automaton (known as template). Parallel composition of such processes forms the description of the system. Variables can be either local (private to a particular automaton) or global (accessible by all the automata). Time-based transitions are put into effect by clocks (a built-in feature for timed automata [1, 16]). Time ranges over a continuous domain and all the clocks declared in a system progress simultaneously. Every automaton has an initial location, denoted by a double circle. Transition from one location to other can be guarded by a boolean expression comprising local and global variables as well as certain clock expressions (e.g., comparing a clock against a constant). During a transition, a process can synchronize with another process (handshaking) or can broadcast a message for multiple recipients using channels.

A location can be marked as committed when the outgoing transition from that location is required to be the only possibility. This technique is helpful to reduce a state space by preventing interleaving with transitions from other processes, i.e., not marked as committed. Furthermore, invariants (conditions) to a location can also be applied and respective invariant is required to be satisfied whenever the automaton is in that location.

UPPAAL provides built-in data types for bounded integers, Booleans, clocks and channels. UPPAAL also supports scalars which are integer-like elements used for symmetry reduction, a technique used in state space reduction [9]. Using scalars, we define (typedef) scalarsets which can be regarded as unordered integer subranges. This technique is helpful when a system model contains multiple symmetrically behaving processes. Allowed operators with scalars of the same type are testing (in)equality (= or ≠) and assignment (:=). Symmetry reduction has been successfully applied in e.g., [5, 14, 6] and in the present paper.

Structure of the paper. All the algorithms are presented informally in Section 2 and formally in Section 3. In Section 4 we describe the functional requirements of the algorithms while Section 5 is devoted to the results. The paper is concluded in Section 6.

2 Algorithms

For fault detection, all the participants make a logical ring and every participant monitors its successor, called its target. This is achieved by sending periodic messages of the form “ARE-YOU-ALIVE?” and expecting timely response of the form “I-AM-ALIVE”. If the target is unresponsive then it is suspected and the successor of the current target becomes the new target. Otherwise, if the target is correct and replies “I-AM-ALIVE” in time then it is pinged again after a period of Δ, which is a waiting time specific to that target. Each algorithm has two tasks, Task1 and Task2, where the former is responsible for sending “ARE-YOU-ALIVE?” messages and the latter receives both “I-AM-ALIVE” from the successors and “ARE-YOU-ALIVE?” messages from the predecessors. Upon receiving “ARE-YOU-ALIVE?”, Task2 immediately replies with “I-AM-ALIVE”.
2.1 Assumptions

The family of algorithms presented in [10] and analyzed in this paper are based on the following assumptions.

1. Communication channels between any two processes are reliable, i.e., messages are not lost after stabilization.
2. A crashed process is permanently halted.
3. $\Pi$ is a set of $n$ processes or participants and every process is aware of the formation of the initial logical ring. Members of $\Pi$ are fixed and hence, no process can join the protocol.
4. For fault detection, one process monitors at most one process at a time.
5. Every process is correct at the start and initially does not suspect any other process.
6. The initial waiting time ($\Delta$), the period in between each two rounds of monitoring for every process, is fixed and a priori known to each participant. For example if a process $p$ monitors another process $q$, then $\Delta_{p,q}$ denotes the time interval for which $p$ has to wait for the reply from $q$.
7. All the participants have symmetric behavior.
8. A process does not send any message to itself.
9. A message sent later can reach the destination earlier than a message sent earlier to the same destination.

2.2 An algorithm for weak completeness

This algorithm, given in Figure 1, forms the basis for the other algorithms in [10]. As mentioned at the outset of this section, the functionality of the process $p$ is divided into two concurrent tasks; $Task1$ is in charge of sending out “ARE-YOU-ALIVE?” messages and suspecting processes that have not replied within a certain time and $Task2$ is in charge of receiving messages and processing (responding to them), if needed. Both tasks run in parallel. $Task1$ waits for the mutex and sends an “ARE-YOU-ALIVE?” message to the current target and signals the mutex. Subsequently, $Task1$ sets the variable $received$ to $false$ and waits for its toggling by $Task2$. $Task1$ waits for a fixed amount of time (initially set to the corresponding $\Delta$ for its target), and if it does not receive a response after the timeout, it suspects its target and moves to monitor the successor of its current target. $Task2$ sets the variable $received$ to $true$ upon receiving any message either from the current target or from any of the already suspected processes. Upon receiving a message from a suspected process, say $q$, by another process $p$, the process(es) in $\{q, ..., pred(target_p)\}$ are no more suspected by $p$ and then $q$ becomes the next target. All the messages of the type “I-AM-ALIVE” are discarded if they are neither from the current target, nor from the suspects.

2.3 An algorithm for eventual weak accuracy

This algorithm, given in Figure 2, is an extension of the algorithm presented in Section 2.2. To provide weak accuracy, the waiting time is adjusted according to the response time of a particular process which is supposed to be correct. Such a process is called leader. In the initialization phase of the protocol, an arbitrary process is named as initial-cand (initial candidate) to become the leader. Eventually the leader is either initial-cand or its immediate correct successor. If some process $p$ is unresponsive to an “ARE-YOU-ALIVE?” message and initial_cand $\in \{succ(p), ..., target_p\}$ then the waiting time for the current target is incremented by one unit of time, i.e., $p$ increments its timeout value $\Delta_{p,target_p}$.

2.4 An algorithm for strong accuracy

This algorithm, given in Figure 3, is also an extension to the basic algorithm given in Section 2.2. According to [10], this algorithm provides strong accuracy, i.e., no correct process is eventually considered as suspected. In this algorithm, there is no leader; hence, each process increases the timeout value for its target when suspected. Using such a scheme, each process makes the timeout value sufficiently large so that it eventually stops suspecting its correct target.
Process\((p)\)
\[
\begin{align*}
\text{target}_p & \leftarrow \text{succ}(p) \\
L_p & \leftarrow \emptyset \\
\forall q \in \Pi : \Delta_{p,q} & \leftarrow \text{default timeout}
\end{align*}
\]

cobegin
\begin{align*}
\llbracket \text{Task1} : \\
\text{loop} & \quad \text{wait} (\text{mutex}_p) \\
& \quad \text{send ARE-YOU-ALIVE? to target}_p \\
& \quad t_{out} \leftarrow \Delta_{p,target}_p \\
& \quad \text{received} \leftarrow \text{false} \\
& \quad \text{signal} (\text{mutex}_p) \\
& \quad \text{delay} (t_{out}) \\
& \quad \text{wait} (\text{mutex}_p) \\
& \quad \text{if not} \ \text{received} \\
& \quad \quad L_p \leftarrow L_p \cup \{\text{target}_p\} \\
& \quad \quad \text{target}_p \leftarrow \text{succ}(\text{target}_p) \\
& \quad \text{end if} \\
& \quad \text{signal} (\text{mutex}_p) \\
\end{align*}
\]
\begin{align*}
\llbracket \text{Task2} : \\
\text{loop} & \quad \text{receive message} \ m \ from \ a \ process \ q \\
& \quad \text{wait} (\text{mutex}_p) \\
& \quad \text{case} \ m = \text{ARE-YOU-ALIVE?} : \\
& \quad \quad \text{send I-AM-ALIVE to} \ q \\
& \quad \quad \text{if} \ q \ \in \ L_p \\
& \quad \quad \quad \ L_p \leftarrow L_p \setminus \{q, \ldots, \text{pred}(\text{target}_p)\} \\
& \quad \quad \quad \ \text{target}_p \leftarrow q \\
& \quad \quad \quad \ \text{received} \leftarrow \text{true} \\
& \quad \quad \text{end if} \\
& \quad m = \text{I-AM-ALIVE} : \\
& \quad \text{case} \\
& \quad \quad q = \text{target}_p : \\
& \quad \quad \quad \ \text{received} \leftarrow \text{true} \\
& \quad \quad q \ \in \ L_p : \\
& \quad \quad \quad \ L_p \leftarrow L_p \setminus \{q, \ldots, \text{pred}(\text{target}_p)\} \\
& \quad \quad \quad \ \text{target}_p \leftarrow q \\
& \quad \quad \quad \ \text{received} \leftarrow \text{true} \\
& \quad \quad \text{else} \ \text{discard} \ m \\
& \quad \text{end case} \\
& \quad \text{end case} \\
& \quad \text{signal} (\text{mutex}_p) \\
\end{align*}
\]
\begin{align*}
\text{coend}
\end{align*}

Fig. 1. Algorithm that provides weak completeness \[10\].

2.5 An algorithm for strong completeness

In this algorithm, given in Figure 4, each participant \(p\) maintains a global list \(G_p\) of suspected processes along with its local view \(L_p\) of suspected processes (the former is particular to this algorithm, while the latter is common to all algorithms). Upon sending and receiving each message of types “ARE-YOU-ALIVE?” and “I-AM-ALIVE”, the global list is sent along and is updated, respectively, i.e., suspected processes are added while the correct ones are removed. In this way, eventually all crashed processes will be aggregated in list \(G\) and correct processes will be removed from \(G\), realizing the goals of the algorithm.

3 Formal Specification in UPPAAL

We specify \textit{Task1}, \textit{Task2}, the communication channels and the monitor processes (explained in Section 5) in terms of timed automata in UPPAAL \[12\]. Parallel composition of these timed automata forms the system model. To alleviate the state-space explosion problem, we apply symmetry reduction \[9\] to our models, because all participants have symmetrical behavior. To this end, we exploit scalar set to specify this symmetric behavior as shown in Figure 5. In this figure, \textit{initAll} is a function for assigning default values (to global declarations) and forming a logical ring of participants. There is a twist in our use of scalar sets \[9\], however, for specifying symmetry in our models. UPPAAL’s scalar sets are suitable for specifying fully symmetric structures; in order to specify symmetry in a ring, we need to identify the next process for each process while not exposing the exact identity of the process, to prevent breaking symmetry. This is the main technical difficulty dealt with in Figure 5. The loops (of type \textit{for}) in the beginning of the \textit{initAll} function are used to make the elements of \(\Pi\) dissimilar to each other.

In the following sections we discuss the formal specification of processes for each algorithm.
initial_cand_p ← pre-agreed process

\[
\text{target}_p ← \text{succ}(p)
\]

\[
L_p ← \emptyset
\]

\[\forall q ∈ P : \Delta_{p,q} ← \text{default timeout}\]

cobegin
  || Task1:
    loop
      wait(mutex_p)
      send ARE-YOU-ALIVE? to target_p
      \(t_{out} ← \Delta_{p,target_p}\)
      received ← false
      signal(mutex_p)
      delay \(t_{out}\)
      \(\Delta_{p,target_p} ← \Delta_{p,target_p} + 1\)
      \(L_p ← L_p \cup \{\text{target}_p\}\)
      \(\text{target}_p ← \text{succ(}\text{target}_p)\)
    end if
    \(\text{target}_p ← \text{succ(}\text{target}_p)\)
  end loop
  || Task2:
    \(\ldots\ \{\text{Same as algorithm in Fig. 1}\}\)
  coend

\[\text{Fig. 2. Algorithm that provides weak accuracy [10].}\]

\[\text{Fig. 3. Algorithm that provides strong accuracy [10].}\]

### 3.1 Weak completeness

**Task1** The automaton for Task1 is shown in Figure 6 where \(p\) is the identifier of the process executing Task1. In the initial state, Task1 waits for the mutex and upon its availability, it assigns target\(_p\) to MyTarget (a temporary variable). This temporary variable is used because target\(_p\) can change, while MyTarget remains constant throughout each given round. Then at the wait state, Task1 synchronizes with the channels dedicated to target\(_p\) and sends an “ARE-YOU-ALIVE?” message. During this synchronization, the mutex is signaled (i.e., released) and received\(_p\) is reset in accordance with the discussion in Section 2.2. At the delay state, Task1 either notices non-deterministically the receipt of an “I-AM-ALIVE” message by Task2 or starts suspecting the current target after reaching the noReply state. The function succ computes the successor of the current target. The process may crash at any state as shown in Figure 6. We assume that a crashed process can only receive messages but will not respond to them; the former assumption is essential, because otherwise messages to crashed processes would not be removed from the channels.

In this protocol, UPPAAL’s built-in support for timed automata is not used, because time plays a role only in determining whether a received message is in time or not (i.e., in distinguishing no reply from late reply), which we model as a non-deterministic choice at the state delay in Figure 6.
Process($p$)

{if the algorithm needs it:
  initial_cand$_p$ ← pre-agreed process
}

target$_p$ ← succ($p$)

$L_p$ ← ∅

$G_p$ ← ∅

$\forall q \in II : \Delta_{p,q} ←$ default timeout

cobegin
  || Task1:
  loop
    wait($mutex_p$)
    send ARE-YOU-ALIVE? to target$_p$
    —with $G_p$ — to target$_p$

    $t_{out} ← \Delta_{p,target_p}$
    received ← false
    signal($mutex_p$)
    delay $t_{out}$
    wait($mutex_p$)

    if not received
      {Update $\Delta_{p,target_p}$ if required}
      $G_p ← G_p \cup \{target_p\}$
      $L_p ← L_p \cup \{target_p\}$
      target$_p$ ← succ(target$_p$)
    end if
    signal($mutex_p$)
  end loop

  || Task2:
  loop
    receive message $m$ from a process $q$
    wait($mutex_p$)

    case
      $m$=ARE-YOU-ALIVE?:
        send I-AM-ALIVE to $q$
        if $q \in L_p$
          $L_p ← L_p \setminus \{q, \ldots, pred(target_p)\}$
          target$_p$ ← $q$
          received ← true
        end if
      $G_p ← G_p \cup \{target_p\}$
      $m$ = I-AM-ALIVE:
        case
          $q = target_p$:
            received ← true
          $q \in L_p$:
            $L_p ← L_p \setminus \{q, \ldots, pred(target_p)\}$
            $G_p ← G_p \cup \{q\}$
            target$_p$ ← $q$
            received ← true
          else discard $m$
        end case
      end case
    end case
  end loop
coend

Fig. 4. Algorithm that provides strong completeness [10].

In our modeling, only one process is allowed to crash, which without loss of generality can be called $p_1$ (note that $p_1$ is not a particular identifier, but is just one of the scalars used in the ring). Hence, every transition going towards the crashed state is guarded with $p_1$. Crash of Task1 is synchronized with Task2 to halt both tasks at the same time.

Task2 Task2 receives either an “ARE-YOU-ALIVE?” (called message type 0) or an “I-AM-ALIVE” (called message type 1) from some process $q$ at its initial state and then waits for the mutex at the wait state as shown in Figure 7. If the mutex is available it reaches the case state where, according to the message type, it either replies by sending an “I-AM-ALIVE” message or updates the suspicion status for process $q$. If process $q$ is suspected by a process $p$, i.e., $L[p][q]$ is true then all the processes in \{q, ..., pred(target$_p$)\} are removed from the list of $p$’s suspects (using stopSuspect function) and its received variable is set to true as shown at the stopSus state in Figure 7. A message of type “I-AM-ALIVE” is discarded if it is neither from the current target nor from an already suspected process.

Communication channels There are two communication channels between each pair of processes for the messages “ARE-YOU-ALIVE?” and “I-AM-ALIVE”. Each channel has a limited buffer size, globally defined for all channels in the system. Source and destination processes are denoted by from and to, respectively as shown in Figure 8. Upon receiving a message every channel increases its local counter, i.e., $msgCounter$ and decreases when a message is delivered. Channels can receive messages until $msgCounter$ reaches the maximum buffer-size (denoted by $BufferSize$). A message is delivered only if there exists some message in the buffer of that channel.
// Global declarations
typedef scalar[3] id_t; // type declaration
id_t p0, p1, p2; // process identifiers
bool mutex[id_t]; // the mutex of each process
id_t target[id_t]; // target of each process
bool L[id_t][id_t]; // list of suspects for each process
void initAll(){
  // To assign p2 a different value from p0
  for (i:id_t){
    if (i!=p0)
      p2=i;
  }
  // To assign p1 a different value from p0 and p2
  for (i:id_t) {
    if (i!=p0 & & i!=p2)
      p1=i;
  }
  // To form a logical ring of participants
  target[p0]=p1;
  target[p1]=p2;
  target[p2]=p0;
  //To assign default value to the mutex of every participant
  mutex[p0]=mutex[p1]=mutex[p2]=true;
  // initialization of L
  for (i:id_t)
    for (j:id_t)
      L[i][j]=false;
}
// initAll ends

Fig. 5. Implementing Ring Symmetry in UPPAAL

An identical channel is used for the messages of type “ARE-YOU-ALIVE?” for each process.

3.2 Weak accuracy
We model this protocol after its stabilization phase, i.e., when there is an upper bound on the
maximum round-trip delay for messages both in the channels and processes, denoted by maxDelta.

Task1 The process for Task1 in this protocol is similar to the one discussed in Section 3.1. The
variable p is the identifier of the process executing this task. However, unlike in Section 3.1, here
we do use the built-in support of UPPAAL for clocks. Every process uses a separate clock for
each of its target processes. When sending an “ARE-YOU-ALIVE?” message, the variable t.out
(for timeout) and the clock linked to the current target are initialized. At the delay state, delay is
exactly up to t.out. This is why all outgoing edges are guarded with waiting[p][MyTarget] = t.out,
except for those modeling process crashes.

After a timeout, if the received flag is not marked as true by Task2 then Task1 reaches a state,
named as noReply where it is determined whether the initial_cand belongs to {succ(p),...,target_p}
or not as shown in Figure 9. If the initial_cand is in the aforementioned set, then Δ for the current
target is incremented by 1 unit of time (provided that Δ < maxDelta).

The other two edges from the delay states are for going to the initial state after a timeout,
when either a reply has been received or the target is crashed.
Fig. 6. Transition system for Task1 in the algorithm that provides weak completeness

Task2 Task2 is exactly the same as the corresponding task discussed in Section 3.1 except for the added invariant to make sure that the processing time remains within maxDelta. This invariant checks the amount of time spent for a received message so that in the remaining time (maximum delay=maxDelta) the received message is processed.

3.3 Strong accuracy

For this algorithm, Task1 discussed in Section 3.2 is slightly modified while Task2 remains intact. The only difference is at the noReply state in Figure 9. There is only one outgoing transition from the noReply state to the initial state. This transition has no guard and updates Δp,\text{target}_p, L_p and target_p as follows:

- Δp,\text{target}_p = Δp,\text{target}_p + 1,
- L[p][MyTarget] = true, and
- target_p = succ(MyTarget).

3.4 Strong completeness

In the specification of this protocol, we declare a global list G for all suspected processes. Hence, Task1 of each process adds its target to G if the target is suspected and Task2 removes the process if a process from this list communicates with its monitoring process. Task1 discussed in Section 3.3 is modified to add the target in G to the only outgoing transition from the noReply state. There is no other change in Task1.

Task2 is also slightly modified by adding the list G, i.e., if an already suspected process q sends an “I-AM-ALIVE” message to a process p, then p removes q from G and likewise, if the received message is of the type “ARE-YOU-ALIVE?” then both p and q are removed from G.

4 General Requirements

The algorithms to implement unreliable failure detectors in partially synchronous systems given in [10] are supposed to satisfy the following requirements.
1. Deadlock freedom: There must not be a deadlock in any protocol provided that at least two processes are correct.
2. Weak completeness: For the protocol discussed in Section 2.2.
3. Eventual weak accuracy: For the protocol discussed in Section 2.3.
4. Strong accuracy: For the protocol discussed in Section 2.4.
5. Strong completeness: For the protocol discussed in Section 2.5.

5 Results

In this section, we report on our analysis results for all four algorithms presented earlier in this paper. For each algorithm, we first discuss the result of deadlock checking in UPPAAL. In order to compare the effectiveness of UPPAAL, we compare its performance with two other model-checking tools, namely, FDR2 [13, 15] and mCRL2[7]. Then, we propose a slight correction of the algorithms to remove the detected deadlock. Finally, we report on the verification of other properties on the corrected algorithms.

5.1 Results for weak completeness

Detecting deadlocks in UPPAAL In UPPAAL, we specify the absence of deadlock throughout the state space by the following formula:

\[ A[] \text{not deadlock} \]

We have used client and server components of UPPAAL 4.1.4 (64 bit, release July 11, 2011) on different machines, i.e., a client on a Windows-based machine and the server on a Unix-based server machine (4 × 2.5 Ghz processor and 64 GB RAM).
Fig. 9. Timed-automata for Task1 in the algorithm that provides weak accuracy

To express eventuality while not breaking symmetry, we devise monitor processes for liveness properties, which we discuss in detail in the following sections. In the remainder of this section, we assume $\Pi = \{p_0, p_1, p_2\}$ and $p_0$, $p_1$, and $p_2$, respectively, form a logical ring.

Figure 10 shows a counter-example where a finite buffer (of an arbitrary size) overflows and as a consequence the protocol encounters a deadlock. Particularly, the buffer used to store “ARE-YOU-ALIVE?” messages overflows due to sending more “ARE-YOU-ALIVE?” messages and receiving less “I-AM-ALIVE” messages. In this deadlock scenario, the process $p_2$ sends “ARE-YOU-ALIVE?” to its target $p_0$ and after a timeout suspects $p_0$. Then $p_2$ receives “I-AM-ALIVE” and stops suspecting $p_0$. Task2 of $p_2$ receives “I-AM-ALIVE” but at that time the mutex is taken by Task1 which sends “ARE-YOU-ALIVE?” to $p_0$ and releases the mutex. Task2 takes the mutex and processes the recently received “I-AM-ALIVE” considering it the reply of the last polling. Up to this point, the process $p_2$ has sent two “ARE-YOU-ALIVE?” messages and received only one reply whereas it is not waiting for any further reply. Rather it is going to send another “ARE-YOU-ALIVE?” for $p_0$. So, due to repeating the above message sequence at $p_2$’s end, the buffer of size $n$ overflows on $n + 1$ iterations as shown in Figure 10. When the buffer is full, Task1 cannot synchronize with the channel after holding the mutex, and due to the unavailability of the mutex, Task2 is also halted, which results in a deadlock for process $p_2$. Process $p_1$ has already crashed, hence the protocol faces a general deadlock.

Detecting deadlocks in FDR2 and mCRL2 FDR2 [15, Chapter 4] is a model checker for models specified in the process algebra CSP [15, Chapter 1]. It allows for automatically tracing deadlocks/livelocks along with safety and liveness properties. mCRL2 [7] (micro Common Representation Language 2) is a process-algebraic language used for formal specification. The basic behavioral constructs of mCRL2 are based on the process algebra ACP (for the Algebra of Communicating Processes) [2]. By extending ACP with abstract data types, the process algebra $\mu$CRL [8], the predecessor of mCRL2, was created. mCRL2 is an extension of $\mu$CRL involving some native abstract data types such as integers, Booleans, reals, lists and sets and behavioral constructs such as multi-actions (to model true-concurrency). The accompanying toolset of mCRL2 supports different analysis techniques, which are used for simulation, linearization (an algebraic transformation resulting in a process suitable for analysis and state space generation), visualiza-
Are You Alive
timeout, suspect p0
stop suspecting p0
I Am Alive
Are You Alive
received by Task2
and wait for mutex
Are You Alive
I Am Alive
Task2 gets mutex and
processes the already re-
ceived IAM ALIVE

Fig. 10. Message sequence chart showing counterexample for buffer overflow

Besides UPPAAL, we model checked the algorithm that provides weak completeness in both FDR2 and mCRL2, and came up with the same counterexample shown in Figures 10 for the occurrence of a deadlock due to buffer overflow. Formal specifications in mCRL2 and FDR2 are given in Appendices A and B, respectively. The reason for modeling this algorithm in FDR2 and mCRL2 is to compare the performance of the three model checkers, i.e., UPPAAL, FDR2 and mCRL2. The reason for not modeling other algorithms in FDR2 and mCRL2 is that built-in support of time is available only in UPPAAL and time-based events in the other three algorithms play a crucial role in their functionality (see sections 2.3, 2.4 and 2.5).

To fix this deadlock, one solution is to use FIFO channels (instead of arbitrary channels allowing for message overtaking), and another solution is to ignore all incoming messages to a channel when its buffer is full. We categorize the behavior of a channel as follows when its message buffer is full.

1. **Channel type B**: Sender waits until there is space for one message.
2. **Channel type R**: Full channel reports “error” message when another message is received.
3. **Channel type I**: Full channel receives and ignores further messages.

In Table 1, we give the results with respect to channel types R and B.

We performed model-checking on a server machine having $32 \times 16 \times 2$ Ghz processor and $32 \times 12$ GB memory. For channel type I, there is no deadlock regardless of buffer size. For buffer size 1, UPPAAL explored 711410029 states in 404 minutes, FDR2 explored 385861073 states in 887 minutes and mCRL2 explored 168491893 states in 451 minutes. Thus, for this case study, throughput-wise (the number of states per second) UPPAAL is the most effective for larger state spaces, while for smaller state spaces, i.e., for the case of channel types B and R, FDR2 takes the lead as shown in Table 1.

In the remainder of this paper, we first remove the above-mentioned deadlock, using a bounded FIFO channel and then proceed to verify the functional properties of the protocols. (The authors of [10] indicated in a personal communication that general channels with the possibility of overtaking are the ones used when designing the protocol, but as demonstrated above this assumption appears to be too general for the protocol to work correctly.)

**Weak completeness** To verify weak completeness for the algorithm discussed in Section 2.2, we devised a monitor process shown in Figure 11. This process moves to the *error* state when the
system oscillates more than a specified number of times (e.g., three times in Figure 11) between suspecting and not suspecting an already crashed process by its correct predecessor. (A more general monitor can be constructed by counting the number of oscillations and checking it against a fixed constant as the guard for the transition to the state labeled error.) The initial state is marked as committed to give it a higher priority over functional steps of the protocol, because using the initAll function, global declarations are initialized and a logical ring of the participants is formed.

After verification, it turns out that the monitor process does detect a counterexample if the number of oscillations is set to one or two. We depict the counter-examples in Figure 12. According to [10], suspecting a crashed process by its correct predecessor must be permanent and hence the reported counter-examples apparently do violate the intuition stated in [10].

![Fig. 11. Transition system for monitor to check weak completeness](image)

The property of weak completeness is satisfied, i.e., eventually a crashed process is suspected by its correct predecessor, but the proof of Theorem 1 in [10] does not appear to be correct; it is claimed there:

\[ \exists t_0 : \forall p \in \text{crashed}, p \text{ has failed at time } t_0 \text{ and } \forall t \geq t_0, p \in L_{\text{corr\_pred}(p)}(t). \]

A counter-example to this claim is shown in the message-sequence charts of Figure 12, where (a) shows the scenario given as the proof of Theorem 1 while (b) and (c) depict the counter-examples to this proof, i.e., exclusion of a crashed process from the list of suspects. Although this exclusion

<table>
<thead>
<tr>
<th>Tool</th>
<th>Buffer Size</th>
<th>Channel type</th>
<th>time</th>
<th>state-space</th>
<th>states/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>mCRL2</td>
<td>1</td>
<td>B</td>
<td>44 sec</td>
<td>588641</td>
<td>13378</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>R</td>
<td>33 sec</td>
<td>314951</td>
<td>9544</td>
</tr>
<tr>
<td>UPPAAL</td>
<td>1</td>
<td>B</td>
<td>52 sec</td>
<td>2431674</td>
<td>46762</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>R</td>
<td>1 sec</td>
<td>167388</td>
<td>167388</td>
</tr>
<tr>
<td>FDR2</td>
<td>1</td>
<td>B</td>
<td>1 sec</td>
<td>167388</td>
<td>167388</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>R</td>
<td>0 sec</td>
<td>2401</td>
<td>2401</td>
</tr>
</tbody>
</table>
is eventually stopped, oscillating between suspecting and not-suspecting a crashed process is not addressed in the proof.

In Figure 12, a correct predecessor of a process $p$ sends an “ARE-YOU-ALIVE?” message to $p$ and receives its reply after which $p$ crashes. At time $t'$, another “ARE-YOU-ALIVE?” message is sent and because of $p$’s crash failure, it is assumed that there will be no further message from $p$. Hence, $p$ is permanently suspected as shown in Figure 12(a) after $\Delta_{\text{correct}, \text{pred}(p), p(t')}$. However, Figure 12(b) shows receiving of a “ARE-YOU-ALIVE?” message (late, due to unbounded delay in channels) from $p$ which causes it to stop suspecting process $p$. Figure 12(c) shows a different situation when $\text{Task2}$ of $\text{corr\_prd}(p)$ receives a “I-AM-ALIVE” message and waits for the mutex but at the same time, timeout occurs at $\text{Task1}$ which adds the process $p$ in suspects and releases the mutex. $\text{Task2}$ takes the mutex and processes the reply, due to which $p$ is again excluded from the list of suspects.

![Counterexamples contradicting Theorem 1 given in [10]](image)

**Fig. 12.** Counterexamples contradicting Theorem 1 given in [10]

### 5.2 Results for weak accuracy

**Deadlock** The counterexample shown in Figure 13 exhibits the deadlock scenario which is different from the one discussed in Section 5.1 but it resembles it in the sense that it is also due to not-suspecting by receiving an “ARE-YOU-ALIVE?” message when an “I-AM-ALIVE” message is expected. An explanation of reaching deadlock in process $p_0$ is given below.

1. Send “ARE-YOU-ALIVE?” to $p_1$, but $p_1$ is already crashed.
2. Suspect $p_1$ and change target to $p_2$. 
4. Timeout and suspect $p_2$.
5. Receive “ARE-YOU-ALIVE?” from $p_2$.
7. Send “ARE-YOU-ALIVE?” to $p_2$.
8. Task2 receives “ARE-YOU-ALIVE?” from $p_2$ and gets the mutex but cannot send “I-AM-ALIVE” because the same message (mentioned at step 6) is already there to be delivered. Now Task2 continues to wait for a free channel while holding the mutex. Because of the mutex, Task1 also stops and as a result the whole process $p_0$ is halted even though it is non-faulty. A similar reason for deadlock is there for $p_2$ as well, which is shown in Figure 13.

![Message sequence chart to show deadlock](image)

Fig. 13. Message sequence chart to show deadlock

Again, the deadlock is removed when replacing the communication channel with a FIFO channel and we verify the rest of the properties in the fixed setting.

**Weak accuracy** To verify weak accuracy, we devised a monitor process shown in Figure 14 and found that this property is satisfied. The initial state is marked committed, so that the first transition in the system model is by this monitor process which uses the initAll function to initialize global variables. Then, it takes the next transition only when the waiting time at some process $p_0$ for process $p_2$ reaches maxDelta whereas in the logical ring of processes $p_0$, $p_1$ and $p_2$ only $p_1$ can crash. So this monitor process reaches the error state when the process $p_2$ is correct, replying within maxDelta and its correct predecessor $p_0$ suspects it.

![Transition system for monitoring weak accuracy](image)

Fig. 14. Transition system for monitoring weak accuracy
5.3 Results for strong accuracy and strong completeness

We found the same deadlock reported in Section 5.2 for both of these algorithms but their concerning properties of strong accuracy and strong completeness are satisfied.

For strong accuracy, we devised a monitor process shown in Figure 15. In the logical ring of the processes $p_0$, $p_1$ and $p_2$, only $p_1$ is allowed to crash. In other words the processes $p_0$ and $p_2$ are correct and according to strong accuracy [10] they are supposed to be not suspected if they continue responding within a certain amount of time. So, the monitor process monitors the suspicion status of both $p_0$ and $p_1$ when the waiting time of one for the other is augmented to $\text{maxDelta}$ but the other is still unresponsive. So, $\Delta$ becomes more than $\text{maxDelta}$, which is a violation of strong accuracy because the upper bound on the round-trip communication between each pair of processes is $\text{maxDelta}$. So, $\forall p, q \in \text{Correct}$ when $\Delta_{p,q}$ becomes greater than $\text{maxDelta}$ then it causes reaching to the error state.

![Fig. 15. Monitor process for strong accuracy](image)

For strong completeness, we devised the monitor process shown in Figure 16. As discussed before, only the process $p_1$ is allowed to crash. So the monitor process shown in Figure 16 reaches to error state when $p_1$ is crashed but not suspected (i.e., not part of the list $G$) while the other processes $p_0$ and $p_2$ have augmented their waiting time to $\text{maxDelta}$.

![Fig. 16. Monitor process for strong completeness](image)

6 Conclusions

We presented formal specification and verification of the algorithms given in [10] to implement unreliable failure detectors in partially synchronous systems. Participants of each algorithm have symmetric behavior, and this allowed us to apply symmetry reduction to overcome the state-space explosion problem.

The results of our verification show that all algorithms contain a deadlock if there is a bounded (yet arbitrarily large) buffer in the communication channel between a pair of nodes. We implement a fix for this problem and show that in the fixed setting, the other claimed properties regarding accuracy and completeness are indeed satisfied by the respective algorithms.

We also used one of the algorithms as a case study to compare the performance of three model-checking tools, namely, UPPAAL, mCRL2 and FDR2. The comparison with respect to exploring number of states per second showed that UPPAAL is best suited for larger state space, e.g., 700 millions states and more whereas for relatively smaller state spaces, e.g., 300 millions or less, the performance of FDR2 is better than both UPPAAL and mCRL2.

Acknowledgements

We are grateful to Jan Friso Groote for his valuable comments and discussions.
References

A mCRL2 specification for the algorithm that provides weak completeness

% Specification of the algorithm that provides weak completeness
% Constants
BufferSize: N;
eqn BufferSize = 1;

% Sort declarations
% This should be pretty much self-explanatory.
sort MsgType = struct Are_You_Alive?isAre_You_Alive|I_Am_Alive?isI_Am_Alive|NULL;

% Mappings
% For an explanation of the functionality, see the description that goes
% with the implementation.
map Succ: N → N;
map Pred: N → N;

var
n : N;
bodList : List(B);
b, b1 : B;
eqn
% To Compute a successor in a logical ring of three processes
Succ(n) = if (n ≈ 2, 0, n + 1);
% To Compute a predecessor in a logical ring of three processes
Pred(n) = if (n == 0, 2, Int2Nat(n - 1));

act
sendToChannel : MsgType × N × N;
rcvAtChannel : MsgType × N × N;
send : MsgType × N × N;
sendToProc : MsgType × N × N;
rcvAtProc : MsgType × N × N;
receive : MsgType × N × N;
crash : N;
suspect : N × N;
stopSuspect : N × N;
replyRcvd : N × N;
discardMsg : N × N;
error;

proc
% rcvdFlag is used when some msg by task2 is rcvd but not yet
% processed then this flag is on otherwise off
% Process for every participant.
% parameters are:
% p: process ID
% target: target of this process
\% sent: a flag used to avoid sending another Are\_you\_Alive message without
\% any action on the first one.
\% received: used to determine the response from the target
\% L: list of suspects
\% m: a message received by task2
\% rcvdFlag: a flag used by task2 when some message is received and task2
\% waits for mutex

\begin{verbatim}
P(p, target : N, sent : B, received : B, L : Set(N), q : N, m : MsgType, rcvdFlag : B) =
\% Task 1
\hfill\textbf{\% Task 1}
\begin{align*}
& \neg\text{sent} \rightarrow \text{sendToChannel}(\text{Are\_you\_Alive}, p, target). P(\text{sent} = \text{true}, \text{received} = \text{false}) \hfill \\
& + \{ \text{sent} \land \neg\text{received} \rightarrow \text{suspect}(p, target). \} \hfill \\
& \text{rcvdFlag} = \text{false} \hfill \\
& \text{sendToChannel}(\text{Are\_you\_Alive}, p, target) \hfill \\
& \text{received} \hfill \\
& \text{stopSuspect}(p, q, target, sent, true, L) \hfill \\
\end{align*}

\% Task 2
\hfill\textbf{\% Task 2}
\begin{align*}
& \neg\text{rcvdFlag} \rightarrow \sum_{m:MsgType} \sum_{\text{sender} : N} \text{rcvAtProc}(m, \text{sender}, p). \hfill \\
& P(m = m, q = \text{sender}, \text{rcvdFlag} = \text{true}) \hfill \\
& + \{ \text{if some msg is received by task2} \} \hfill \\
& \text{rcvdFlag} = \text{true} \hfill \\
& \text{rcvAtProc}(m, \text{sender}, p). \hfill \\
& \text{received} \hfill \\
& \text{stopSuspect}(p, q, target, sent, true, L) \hfill \\
\end{align*}

\% isAre\_you\_Alive(m) \rightarrow \text{sendToChannel}(\text{Is\_Am\_Alive}, p, q).
\begin{align*}
& \text{received} \hfill \\
& \text{stopSuspect}(p, q, target, sent, true, L) \hfill \\
\end{align*}

\% if q != target and q not in Lp then
\begin{align*}
& + \{ \text{discard msg (i.e., both cases are false)} \} \hfill \\
& \text{discardMsg}(q, p). P(\text{rcvdFlag} = \text{false}) \hfill \\
\end{align*}

\% a process to exclude all suspects processes from L which are in
\% \{q \ldots, \text{pred}(target p)\} where q is the sender of last message
\% parameters are same as define for process P

\begin{verbatim}
\text{stopSuspect}(p, q, target : N, m : MsgType) =
\begin{align*}
& \text{stopSuspect}(p, q). (\text{Pred}(target) \in L - \{q\}) \rightarrow \text{stopSuspect}(p, \text{Pred}(target)). \hfill \\
& P(p, q, false, true, \{\}, 0, NULL, false) \hfill \\
& + \{ P(p, q, false, true, L - \{q\}, 0, NULL, false); \} \hfill \\
\end{align*}
\end{verbatim}

\% CHANNEL
\% Channel from one process to other w.r.t. each msg type.
\% Parameter names are self explanatory.
\begin{verbatim}
\text{Channel}(\text{from}, \text{to}, \text{msgCounter} : N, m : \text{MsgType}) =
\begin{align*}
& \text{Channel}(\text{msgCounter} = \text{msgCounter} + 1) \hfill \\
& \text{rcvAtChannel}(m, \text{from}, \text{to}). \text{Channel}() \hfill \\
\end{align*}
\end{verbatim}

\% \text{msgCounter} > 0 \rightarrow \text{sendToProc}(m, \text{from}, \text{to}).
\begin{verbatim}
\text{Channel}(\text{msgCounter} = \text{Int2Nat}(\text{msgCounter} - 1)) \hfill \\
\end{verbatim}

\% Protocol
\begin{verbatim}
\text{Protocol} =
\n\text{\Gamma}(
\begin{array}{c}
\text{send, receive, crash, suspect, stopSuspect, replyRcvd, discardMsg} \\
\end{array}
\);)
\end{verbatim}

\% \text{sendToChannel | \text{rcvAtChannel \rightarrow send, sendToProc | \text{rcvAtProc \rightarrow receive}}

Channel(0, 1, 0, Are_You_Alive) ||
Channel(1, 0, 0, I_Am_Alive) ||
Channel(0, 2, 0, Are_You_Alive) ||
Channel(2, 0, 0, I_Am_Alive) ||
Channel(1, 2, 0, Are_You_Alive) ||
Channel(2, 1, 0, I_Am_Alive) ||
Channel(1, 0, 0, Are_You_Alive) ||
Channel(0, 1, 0, I_Am_Alive) ||
Channel(2, 1, 0, Are_You_Alive) ||
Channel(1, 2, 0, I_Am_Alive) ||
Channel(2, 0, 0, Are_You_Alive) ||
Channel(0, 2, 0, I_Am_Alive) ||
Channel(1, 0, 0, Are_You_Alive) ||
Channel(0, 1, 0, I_Am_Alive) ||
Channel(2, 1, 0, Are_You_Alive) ||
Channel(1, 2, 0, I_Am_Alive) ||
Channel(2, 0, 0, Are_You_Alive) ||
Channel(0, 2, 0, I_Am_Alive)

"

init;

Protocol;
B FDR2 specification for the algorithm that provides weak completeness

Note: In the following type settings \(\rightarrow\) is replaced by \(\to\)

```
datatype MyAlphabets = Are_You_Alive | I_Am_Alive
Msg={Are_You_Alive, I_Am_Alive}
Processes=\{0,1,2\}
BufferSize=1
channel sendToChannel,rcvAtProc: Processes . Processes . Msg
channel suspect,stopSuspect: Processes . Processes
channel crash : Processes
channel queue_full : Processes . Processes

Channel(from,to,msgCounter,m)=
    (msgCounter<BufferSize)\& sendToChannel(from.to.m \to Channel(from.to,msgCounter+1,m))
    --- ignore extra signals
    (msgCounter>0) \& rcvAtProc(from.to.m \to Channel(from.to,msgCounter-1,m))
    --- report queue full and stop
    (msgCounter==BufferSize)\& sendToChannel(from.to.m \to queue_full(from.to \to STOP)
Buffer(from.to,c,m) = Channel(from.to,c,m)

P(p,target)=
    let Proc(target,sent,received,L)=
    --- Task 1
    (not sent and target\(!=p)\& sendToChannel.p.target.Are_You_Alive \to Proc(target,true,false, L)
    (sent and not(received))\& suspect.p.target \to Proc(succ(target),false,false, union(L,{target})))
    --- Task 2
    if (Are_You_Alive==m) then (sendToChannel.p.q.I_Am_Alive \to Proc(target,true,false, L)
    else
        Proc(target,sent,true,L)
    )
    if (q==target) then Proc(target,false,true,L)
    else Proc(target,sent,received,L)
    )
    (p==1)\& crash.p \to CrashedProc(p)

CrashedProc(p)= [][m:Msg,from:Processes \& rcvAtProc.q.p.m] 
    StopSus(p.q,target,sent,received,L)
    ( stopSuspect.p.q \to if member(pred(target), diff(L,\{q\})) then stopSuspect.p.pred(target) \to Proc(q,false,true,\{\})
    else Proc(q,false,true,diff(L,\{q\}))
    )
    within Proc(target,false,false, \{})

succ(n)\=(n + 1)\%(\card(Processes))
next(n)\=if n=0 then (\card(Processes)-1)
else n-1
```
--- define a process with its buffers
\[ P_{Bs}(x) = (((P(x, succ(x)) \|\{sendToChannel()}\| (\| m:Msg, y:dif(Processes,\{x\}) \\
\| Buffer(x,y,0,m)) \})) \]

--- Put process 0 and 1 together
TwoProcesses = \( P_{Bs}(0) \| \{rcvAtProc.0.1, rcvAtProc.1.0, rcvAtProc.0.0, rcvAtProc.1.1 \\
, rcvAtProc.2.2 \\
\} \| P_{Bs}(1)) \)

--- Put process 2 with process 0 and 1 together
ThreeProcesses = \( (\{TwoProcesses \| \{rcvAtProc.1.2, rcvAtProc.2.1, rcvAtProc.0.2, rcvAtProc.2.0 \\
\} \| P_{Bs}(2)) \)

--- property weak completeness
Spec1= (suspect.0.1 \rightarrow Spec1) \| crash.1 \rightarrow Suspecting

--- number of suspect.0.1 events depends on the size of buffer.
--- p0 should suspect 1 only one time.
--- Suspecting= (suspect.0.1 \rightarrow suspect.0.1 \rightarrow STOP)

Protocol = ThreeProcesses \| \{\{crash.1, suspect.0.1 \|\} \}

--- check and report queue full
assert STOP [T= ThreeProcesses \| \{\{queue_full\} \}]

--- check weak completeness property, counterexample is produced
--- indicating that p1 is suspected twice.
assert Spec1 [T= Protocol
assert Spec1 [F= Protocol