Modelling and Simulation of Asynchronous Real-Time Systems using Timed Rebeca

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In this paper we propose an extension of the Rebeca language that can be used to model distributed and asynchronous systems with timing constraints. We provide the formal semantics of the language using Structural Operational Semantics, and show its expressiveness by means of examples. We developed a tool for automated translation from timed Rebeca to the Erlang language, which provides a first implementation of timed Rebeca. We can use the tool to set the parameters of timed Rebeca models, which represent the environment and component variables, and use McErlang to run multiple simulations for different settings. Timed Rebeca restricts the modeller to a pure asynchronous actor-based paradigm, where the structure of the model represents the service oriented architecture, while the computational model matches the network infrastructure. Simulation is shown to be an effective analysis support, specially where model checking faces almost immediate state explosion in an asynchronous setting.

1   Introduction

This paper presents an extension of the actor-based Rebeca language [22] that can be used to model distributed and asynchronous systems with timing constraints. This extension of Rebeca is motivated by the ubiquitous presence of real-time computing systems, whose behaviour depends crucially on timing as well as functional requirements.

A well-established paradigm for modelling the functional behaviour of distributed and asynchronous systems is the actor model. This model was originally introduced by Hewitt [8] as an agent-based language, and is a mathematical model of concurrent computation that treats *actors* as the universal primitives of concurrent computation [1]. In response to a message that it receives, an actor can make local decisions, create more actors, send more messages, and determine how to respond to the next message it receives. Actors have encapsulated states and behaviour, and are capable of redirecting communication links through the exchange of actor identities. Different interpretations, dialects and extensions of actor models have been proposed in several domains and are claimed to be the most suitable model of computation for the dominating applications, such as multi-core programming and web services [9].

Reactive Objects Language, *Rebeca* [22], is an operational interpretation of the actor model with formal semantics and model-checking tools. Rebeca is designed to bridge the gap between formal methods and software engineers. The formal semantics of Rebeca is a solid basis for its formal verification. Compositional and modular verification, abstraction, symmetry and partial-order reduction have been investigated for verifying Rebeca models. The theory

underlying these verification methods is already established and is embodied in verification tools [14, 21, 22]. With its simple, message-driven and object-based computational model, Java-like syntax, and a set of verification tools, Rebeca is an interesting and easy-to-learn model for practitioners.

Motivation and Contribution.   Although actors are attracting more and more attention both in academia and industry, little has been done on timed actors and even less on analyzing timed actor-based models. In this work we present

- timed Rebeca by extending Rebeca with time constraints,
- the formal semantics of timed Rebeca using Structural Operational Semantics (SOS) [19],
- a tool for mapping timed Rebeca models to Erlang, and
- experimental results from the simulation of timed Rebeca models using McErlang [7].

The contribution of this work is offering a pure asynchronous actor-based modelling language with timing primitives and analysis support. Timed Rebeca can be used in a model-driven methodology in which the designer builds an abstract model where each component is a reactive object communicating through non-blocking asynchronous messages. The structure of the model can very well represent service oriented architectures, while the computational model matches the network infrastructure. Hence the model captures faithfully the behaviour of the system in a distributed and asynchronous world.

Comparison with other timed models.   Comparing with the well-established timed models, like timed automata [2], TCCS [25], and real-time Maude [18], timed Rebeca offers an actor-based syntax and a built-in actor-based computational model, which restricts the style of modelling to an event-based concurrent object-based paradigm. Modelling time-related features in computational models has been studied for a long time [3, 2]; while we have no claims of improving the expressiveness of timed models, we believe that our model is highly usable due to its actor-based nature and Java-like syntax. The usability is due to the one to one correspondence between the entities of the real world and the objects in the model, and the events and actions of the real world and the computational model. Moreover, the syntax of the language is familiar for software engineers and practitioners.

Comparison with other timed actor models.   We know of a few other timed actor-based modelling languages [20, 16, 4] that we will explain in more detail in the related work section. In [20] a central synchronizer acts like a coordinator and enforces the real-time and synchronization constraints (called interaction constraints). The language for the coordinated actors is briefly proposed in [16]; however, the main focus is having reusable real-time actors without hardwired interaction constraints. The constraints declared within the central synchronizer in this line of work can be seen as the required global properties of a timed Rebeca model. We capture the architecture and configuration of a system via a timed Rebeca model and then we can check whether the global constraints are satisfied. The language primitives that we use to extend Rebeca are consistent with the proposal in [16]. The primitives proposed in [4] are different from ours; they introduced an *await* primitive where we keep the asynchronous nature of the model.

Analysis support. In order to analyze timed Rebeca models, we developed a tool to facilitate their simulation. In a parallel project [11], a mapping from timed Rebeca to timed automata is developed and UPPAAL [24] is used for model checking. The asynchronous nature of Rebeca models causes state explosion while model checking even for small models. One solution is using a modular approach like in [12]. Here, we selected an alternative solution as a complementary tool for analysis. Using our tool we can translate a timed Rebeca model to Erlang [6], set the parameters which represent the environment and component variables, and run McErlang [7] to simulate the model. The tool allows us to change the settings of different timing parameters and rerun the simulation in order to investigate different scenarios, find potential bugs and problems, and optimize the model by manipulating the settings. The parameters can be timing constraints on the local computations (e.g., deadlines for accomplishing a requested service), computation time for providing a service, and frequency of a periodic event. Parameters can also represent network configurations and delays. In our experiments we could find timing problems that caused missing a deadline, or an unstable state in the system.

The formal semantics presented in this paper is the basis for the correct mapping from timed Rebeca to Erlang. The detailed mapping, and the tool together with some examples can be found at [10].

Our choice to use the actor-based programming language Erlang is also based on the idea of covering the whole life cycle of the system in future, and of providing a refinement step for implementing the code from our timed Rebeca model.

2   Related Work

Different approaches are used in designing formal modelling languages for real-time systems. The model of timed automata, introduced by Alur and Dill [2], has established itself as a classic formalism for modelling real-time systems. The theory of timed automata is a timed extension of automata theory, using clock constraints on both locations and transitions. In many other cases the proposed modelling languages for real-time systems are extensions of existing languages with real-time concepts—see, for example, TCCS [25] and Real-time Maude [18].

A real-time actor model, RT-synchronizer, is proposed in [20], where a centralized synchronizer is responsible for enforcing real-time relations between events. Actors are extended with timing assumptions, and the functional behaviours of actors and the timing constraints on patterns of actor invocation are separated. The semantics for the timed actor-based language is given in [16]. Two positive real-valued constants, called *release time* and *deadline*, are added to the *send* statement and are considered as the earliest and latest time when the message can be invoked relative to the time that the method executing the send is invoked. In Timed Rebeca, we have the constructs *after* and *deadline*, which are representing the same concepts, respectively, except that they are relative to the time that the message (itself) is sent. So, it more directly reflects the computation architecture including the network delays. In our language, it is also possible to consider a time *delay* in the execution of a computation where in [16] it is possible to specify an upper bound on the execution time of a method. While RT-synchronizer is an abstraction mechanism for the declarative specification of timing constraints over groups of actors, our model allows us to work at a lower level of abstraction. Using timed Rebeca, a modeller can easily capture the functional features of a system, together with the timing constraints for both computation and network latencies, and analyze the model from various

points of view.

There is also some work on schedulability analysis of actors [17], but this is not applied on a real-time actor language. Time constraints are considered separately. Recently, there have been some studies on schedulability analysis for Rebeca models [13]. This work is based on mapping Rebeca models to timed automata and using UPPAAL to check the schedulability of the resulting models. Deadlines are defined for accomplishing a service and each task spends a certain amount of time for execution. In the above-mentioned papers, modelling of time is not incorporated in the Rebeca language.

Creol is a concurrent object-oriented language with an operational semantics written in an actor-based style, and supported by a language interpreter in the Maude system. In [5], Creol is extended by adding best-case and worst-case execution time for each statement, and a deadline for each method call. In addition, an object is assigned a scheduling strategy to resolve the nondeterminism in selecting from the enabled processes. This work is along the same lines as the one presented in [13] and the focus is on schedulability analysis, which is carried out in a modular way in two steps: first one models an individual object and its behavioural interface as timed automata, and then one uses UPPAAL to check the schedulability considering the specified execution times and the deadlines. In this work, network delays are not considered, and the execution time is weaved together with the statements in a fine-grained way.

In [4] a timed version of Creol is presented in which the only additional syntax is read-only access to the global clock, plus adding a data-type *Time* together with its accompanying operators to the language. Timed behaviour is modelled by manipulating the *Time* variables and via the *await* statement in the language.

3   Timed Rebeca

A Rebeca model consists of a set of *reactive classes* and the *main* program in which we declare reactive objects, or rebecs, as instances of *reactive classes*. A reactive class has an argument of type integer, which denotes the length of its message queue. The body of the reactive class includes the declaration for its *known rebecs*, variables, and methods (also called message servers). Each method body consists of the declaration of local variables and a sequence of statements, which can be assignments, *if* statements, rebec creation (using the keyword *new*), and method calls. Method calls are sending asynchronous messages to other rebecs (or to self) to invoke the corresponding message server (method). Message passing is fair, and messages addressed to a rebec are stored in its message queue. The computation takes place by taking the message from the front of the message queue and executing the corresponding message server [22].

Timing features in an asynchronous and distributed setting.   To decide on the timing primitives to be added to the Rebeca syntax, we first considered the different timing features that a modeller might need to address in a message-based, asynchronous and distributed setting. These features (like the computation time, or periodic events) can be common in any setting.

1. **Computation time**: the time needed for a computation to take place.

2. **Message delivery time**: the time needed for a message to travel between two objects, that depends on the network delay (and possibly other parameters).

3. **Message expiration**: the time within which a message is still valid. The message can be a request or a reply to a request (a request being served).

4. **Periods of occurrences of events**: the time periods for periodic events.

We introduce an extension of Rebeca with real-time primitives to be able to address the above-mentioned timing features. In timed Rebeca model, each rebec has its own local clock, which can be considered as synchronized distributed clocks[1]. Methods are still executed atomically, but we can model passing of time while executing a method. Instead of a message queue for each rebec, we have a bag containing the messages that are sent. The timing primitives that are added to the syntax of Rebeca are *delay*, *now*, *deadline* and *after*. Figure 1 shows the grammar for Timed Rebeca. The *delay* statement models the passing of time for a rebec during execution of a method (computation time), and *now* returns the local time of the rebec. The keywords *after* and *deadline* can only be used in conjunction with a method call. Each rebec knows about its local time and can put *deadline* on the messages that are sent declaring that the message will not be valid after the deadline (modelling the message expiration). The *after* primitive, attached to a message, can be used to declare a constraint on the earliest time at which the message can be served (taken from the message bag by the receiver rebec). The modeller may use these constraints for various purposes, such as modelling the network delay or modelling a periodic event.

The messages that are sent are put in the message bag together with their time tag and *deadline* tag. The scheduler decides which message is to be executed next based on the time tags of the messages. The time tag of a message is the value of *now* when the message was sent, with the value of the argument of the *after* added to it when the message is augmented with an *after*. The intuition is that a message cannot be taken (served) before the time that the time tag determines.

The progress of time is modeled locally by the delay statement. Each delay statement within a method body increases the value of the local time (variable *now*) of the respective rebec by the amount of its argument. When we reach a *call* statement (sending a message), we put that message in the message bag augmented with a time tag. The local time of a rebec can also be increased when we take a message from the bag to execute the corresponding method.

The scheduler takes a message from the message bag, executes the corresponding message server atomically, and then takes another message. Every time the scheduler takes a message for execution, it chooses a message with the least time tag. Before the execution of the corresponding method starts, the local time (*now*) of the receiver rebec is set to the maximum value between its current time and the time tag of the message. The current local time of each rebec is the value of *now*. This value is frozen when the method execution ends until the next method of the same rebec is taken for execution.

The arguments of *after* and *delay* are relative values, but when the corresponding messages are put in the message bag their tags are absolute values, which are computed by adding the relative values of the arguments to the value of the variable *now* of the sender rebec (where the messages are sent). To summarize, Timed Rebeca extends Rebeca with the following four constructs.

- **Delay**: *delay(t)*, where t is a positive natural number, will increase the value of the local clock of the respective rebec by the amount t.

---

[1]In this paper we do not address the problem of distributed clock synchronization; several options and protocols for establishing clock synchronization in a distributed system are discussed in the literature, including [23].

$Model ::= EnvVar^* \ Class^* \ Main \qquad EnvVar ::= \textbf{env} \ T \ \langle v \rangle^+;$

$Main ::= \textbf{main} \ \{ \ InstanceDcl^* \ \} \qquad InstanceDcl ::= C \ r(\langle r \rangle^*) : (\langle c \rangle^*);$

$Class ::= \textbf{reactiveclass} \ C \ \{ \ KnownRebecs \ Vars \ MsgSrv^* \ \}$

$KnownRebecs ::= \textbf{knownrebecs} \ \{ \ VarDcl^* \ \} \ Vars ::= \textbf{statevars} \ \{ \ VarDcl^* \ \} \ VarDcl ::= T \ \langle v \rangle^+;$

$MsgSrv ::= \textbf{msgsrv} \ M(\langle T \ v \rangle^*) \ \{ \ Stmt^* \ \}$

$Stmt ::= v = e; \ | \ r = new \ C(\langle e \rangle^*); \ | \ Call; \ | \ if \ (e) \ MSt \ [else \ MSt] \ | \ \textbf{delay}(t); \ | \ \textbf{now}();$

$Call ::= r.M(\langle e \rangle^*) \ [\textbf{after}(t)] \ [\textbf{deadline}(t)]$

$MSt ::= \{ \ Stmt^* \ \} \ | \ Stmt$

Figure 1: Abstract syntax of Timed Rebeca. Angle brackets $\langle ... \rangle$ are used as meta parenthesis, superscript + for repetition more than once, superscript * for repetition zero or more times, whereas using $\langle ... \rangle$ with repetition denotes a comma separated list. Brackets [...] show being optional. Identifiers $C, T, M, v, c,$ and r denote class, type, method, variable, constant, and rebec names, respectively; and e denotes an (arithmetic, boolean or nondetermistic choice) expression.

- **Now**: *now()* returns the time of the local clock of the rebec from which it is called.

- **Deadline**: *r.m() deadline(t)*, where *r* denotes a rebec name, *m* denotes a method name of *r* and *t* is a natural number, means that the message *m* is sent to the rebec *r* and is put in the message bag. After *t* units of time the message is not valid any more and is purged from the bag. Deadlines are used to model message expirations (timeouts).

- **After**: *r.m() after(t)*, where *r* denotes a rebec name, *m* denotes a method name of *r* and *t* is a natural number, means that the message *m* is sent to the rebec *r* and is put in the message bag. The message cannot be taken from the bag before *t* time units have passed. After statements can be used to model network delays in delivering a message to the destination, and also periodic events.

Ticket Service Example We use a ticket service as a running example throughout the article. Listing 1 shows this example written in Timed Rebeca. The ticket service model consists of two reactive classes: *Agent* and *TicketService*. Two rebecs, *ts*1 and *ts*2, are instantiated from the reactive class *TicketService*, and one rebec *a* is instantiated from the reactive class *Agent*. The agent *a* is initialized by sending a message *findTicket* to itself in which a message *requestTicket* is sent to the ticket service *ts*1 or *ts*2 based on the parameter passed to *findTicket*. The deadline for the message *requestTicket* to be served is *requestDeadline* time units. Then, after *checkIssuedPeriod* time units the agent will check if it has received a reply to its request by sending a *checkTicket* message to itself, modelling a periodic event. There is no receive statement in Rebeca, and all the computation is modeled via asynchronous message passing, so, we need a periodic check. The *attemptCount* variable helps the agent to keep track of the ticket service rebec that the request is sent to. The *token* variable allows the agent to keep track of which incoming *ticketIssued* message is a reply to a valid request. When any of the ticket service rebecs receives the *requestTicket* message, it will issue the ticket after *serviceTime1* or *serviceTime2* time units, which is modelled by sending *ticketIssued* to the agent with the *token* as parameter. The

expression ?(*serviceTime*1,*serviceTime*2) denotes a nondeterministic choice between *serviceTime*1 and *serviceTime*2 in the *assignment* statement. Depending on the chosen value, the ticket service may or may not be on time for its reply.

```
1   env int requestDeadline, checkIssuedPeriod, retryRequestPeriod, newRequestPeriod, serviceTime1,
        serviceTime2;
2
3   reactiveclass Agent {
4     knownrebecs { TicketService ts1; TicketService ts2; }
5     statevars { int attemptCount; boolean ticketIssued; int token; }
6     msgsrv initial() { self.findTicket(ts1); } // initialize system, check 1st ticket service
7     msgsrv findTicket(TicketService ts) {
8       attemptCount += 1; token += 1;
9       ts.requestTicket(token) deadline(requestDeadline); // send request to the TicketService
10      self.checkTicket() after(checkIssuedPeriod); // check if the request is replied
11    }
12    msgsrv ticketIssued(int tok) { if (token == tok) { ticketIssued = true; } }
13    msgsrv checkTicket() {
14      if (!ticketIssued && attemptCount == 1) {        // no ticket from 1st service,
15        self.findTicket(ts2);                          // try the second TicketService
16      } else if (!ticketIssued && attemptCount == 2) { // no ticket from 2nd service,
17        self.retry() after(retryRequestPeriod);        // restart from the first TicketService
18      } else if (ticketIssued) {                       // the second TicketService replied,
19        ticketIssued = false;
20        self.retry() after(newRequestPeriod);          // new request by a customer
21      }
22    }
23    msgsrv retry() {
24      attemptCount = 0; self.findTicket(ts1);     // restart from the first TicketService
25    }
26  }
27
28  reactiveclass TicketService {
29    knownrebecs { Agent a; }
30    msgsrv initial() { }
31    msgsrv requestTicket(int token) {
32      int wait = ?(serviceTime1,serviceTime2);   // the ticket service sends the reply
33      delay(wait);                               // after a non-determinstic delay of
34      a.ticketIssued(token);                     // either serviceTime1 or serviceTime2
35    }
36  }
37
38  main {
39    Agent a(ts1, ts2):();               // instantiate agent, with two known rebecs
40    TicketService ts1(a):();            // instantiate 1st and 2nd ticket services, with
41    TicketService ts2(a):();            // the agent as their known rebecs
42  }
```

Listing 1: A Timed Rebeca model of the ticket service example

3.1 Structural Operational Semantics for Timed Rebeca

In this section we provide an SOS semantics for Timed Rebeca in the style of Plotkin [19]. The behaviour of Timed Rebeca programs is described by means of the transition relation → that describes the evolution of the system.

The states of the system are pairs (*Env*,*B*), where *Env* is a finite set of environments and *B* is a bag of messages. For each rebec *A* of the program there is an environment σ_A contained in *Env*, that is a function that maps variables to their values. The environment σ_A represents the private store of the rebec *A*. Besides the user-defined variables, environments also contain

the value for the special variables *self*, the name of the rebec, *now*, the current time, and *sender*, which keeps track of the rebec that invoked the method that is currently being executed. The environment σ_A also maps every method name of A to its body.

The bag contains an unordered collection of messages. Each message is a tuple of the form $(A_i, m(\overline{v}), A_j, TT, DL)$. Intuitively, such a tuple says that at time TT the sender A_j sent the message to the rebec A_i asking it to execute its method m with actual parameters $\overline{v}$. Moreover this message expires at time DL.

The system transition relation $\rightarrow$ is defined by the rule *scheduler*:

$$(scheduler) \quad \frac{(\sigma_{A_i}(m), \sigma_{A_i}[now = \max(TT, \sigma_{A_i}(now)), [\overline{arg} = \overline{v}], sender = A_j], Env, B) \xrightarrow{\tau} (\sigma'_{A_i}, Env', B')}{(\{\sigma_{A_i}\} \cup Env, \{(A_i, m(\overline{v}), A_j, TT, DL)\} \cup B) \rightarrow (\{\sigma'_{A_i}\} \cup Env', B')} \quad C$$

where the condition C is defined as follows: σ_{A_i} is not contained in *Env*, and $(A_i, m(\overline{v}), A_j, TT, DL) \notin B$, and $\sigma_{A_i}(now) \leq DL$, and $TT \leq \min(B)$. The *scheduler* rule allows the system to progress by picking up messages from the bag and executing the corresponding methods. The third side condition of the rule, namely $\sigma_{A_i}(now) \leq DL$, checks whether the selected message carries an expired deadline, in which case the condition is not satisfied and the message cannot be picked. The last side condition is the predicate $TT \leq min(B)$, which shows that the time tag TT of the selected message has been the smallest time tag of all the messages for all the rebecs A_i in the bag B. The premise executes the method m, as described by the transition relation $\xrightarrow{\tau}$, which will be defined below. The method body is looked up in the environment of A_i and is executed in the environment of A_i modified as follows: (1) The variable *sender* is set to the sender of the message. (2) In executing the method m, the formal parameters $\overline{arg}$ are set to the values of the actual parameters $\overline{v}$. Methods of arity n are supposed to have $arg_1, arg_2, \ldots, arg_n$ as formal parameters. This is without loss of generality since such a change of variable names can be performed in a pre-processing step for any program. (3) The variable *now* is set to the maximum between the current time of the rebec and the time tag of the selected message.

The execution of the methods of rebec A_i may change the private store of the rebec A_i, the bag B by adding messages to it and the list of environments by creating new rebecs through *new* statements. Once a method is executed to completion, the resulting bag and list of environments are used to continue the progress of the whole system.

The transition relation $\xrightarrow{\tau}$ describes the execution of methods in the style of natural semantics [15]. (See Figure 2 for selected rules. The full set of rules may be found in Appendix A.) Since in this kind of semantics the whole computation of a method is performed in a single step, this choice perfectly reflects the atomic execution of methods underlying the semantics of the Rebeca language. The general form of this type of transition is $(S, \sigma, Env, B) \xrightarrow{\tau} (\sigma', Env', B')$. A single step of $\xrightarrow{\tau}$ consumes all the code S and provides the value resulting from its execution. Carrying the bag B is important because new messages may be added to it during the execution of a statement S. Also *Env* is required because *new* statements create new rebecs and may therefore add new environments to it. In the semantics, the local environment σ is separated from the environment list *Env* for the sake of clarity. The result of the execution of the method thus amounts to the modified private store σ', the new list of environments *Env'* and the new bag B'.

The rules for assignment, conditional statement and sequential composition are standard. The rules for the timing primitives deserve some explanation.

(msg) $(varname.m(\bar{v})\ after(d)\ deadline(DL),\sigma,Env,B)$

$\xrightarrow{\tau} (\sigma,Env,\{(\sigma(varname),m(eval(\bar{v},\sigma)),\sigma(self),\sigma(now)+d,\sigma(now)+DL)\}\cup B)$

$(delay)$ $(delay(d),\sigma,Env,B)\xrightarrow{\tau}(\sigma[now=\sigma(now)+d],Env,B)$

$(create)$ $(varname=new\ O(\bar{v}),\sigma,Env,B)$

$\xrightarrow{\tau}(\sigma[varname=A],\{\sigma_A[now=\sigma(now),\ self=A]\}\cup Env,\{(A,initial(eval(\bar{v},\sigma)),\sigma(self),\sigma(now),+\infty)\}\cup B)$

Figure 2: Selected Method-Execution Transition Rules. In rule *create*, the rebec name A should not appear in the range of the environment σ. The function *eval* evaluates expressions in a given environment in the expected way. In each rule, we assume that σ is not contained in *Env*.

- Rule *msg* describes the effect of method invocation statements. For the sake of brevity, we limit ourselves to presenting the rule for method invocation statements that involve both the *after* and *deadline* keywords. The semantics of instances of that statement without those keywords can be handled as special cases of that rule by setting the argument of *after* to zero and that of *deadline* to $+\infty$, meaning that the message never expires. Method invocation statements put a new message in the bag, taking care of properly setting its fields. In particular the time tag for the message is the current local time, which is the value of the variable *now*, plus the number d that is the parameter of the *after* keyword.

- Delay statements change the private variable *now* for the considered rebec.

Finally, the creation of new rebecs is handled by the rule *create*. A fresh name A is used to identify the newly created rebec and is assigned to *varname*. A new environment σ_A is added to the list of environments. At creation time, σ_A is set to have its method names associated to their code. A message is put in the bag in order to execute the *initial* method of the newly created rebec.

4 Mapping from Timed Rebeca to Erlang

In this section, we present a translation from the fragment of Timed Rebeca without rebec creation to Erlang (for an extended explanation and a more formal description see [10]). The motivation for translating Timed Rebeca models to Erlang code is to be able to use McErlang [7] to run experiments on the models. This translation also yields a first implementation of Timed Rebeca.

McErlang is a model-checking tool written in Erlang to verify distributed programs written in Erlang. It supports Erlang datatypes, process communication, fault detection and fault tolerance and the Open Telecom Platform (OTP) library, which is used by most Erlang programs. The verification methods range from complete state-based exploration to simulation, with specifications written as LTL formulae or hand-coded runtime monitors. This paper focuses on simulation since model checking with real-time semantics is not yet offered by McErlang. Note, however, that our translation opens the possibility of model checking (untimed) Rebeca models using McErlang, which is not the subject of this paper.

```
1  receive
2    Pattern1 when Guard1 -> Expr1;
3    Pattern2 when Guard2 -> Expr2;
4    ...
5  after
6    Time -> Expr
7  end
```

Listing 2: Syntax of a receive with timeout.

Erlang Primer   Erlang is a dynamically-typed general-purpose programming language, which was designed for the implementation of distributed, real-time and fault-tolerant applications. Originally, Erlang was mostly used for telephony applications such as switches. Its concurrency model is based on the actor model.

Erlang has few concurrency and timing primitives:

- `Pid = spawn(Fun)` creates a new process that evaluates the given function `Fun` in parallel with the process that invoked spawn.

- `Pid !Msg` sends the given message `Msg` to the process with the identifier `Pid`.

- `receive ... end` receives a message that has been sent to a process; message discrimination is based on pattern matching.

- `after` is used in conjunction with a `receive` and is followed by a timeout block as shown in Listing 2, after the specified time (deadline for receiving the required pattern) the process executes the timeout block

- `erlang:now()` returns the current time of the process

When a process reaches a `receive` expression it looks in the queue and takes a message that matches the pattern if the corresponding guard is true. A guard is a boolean expression, which can include the variables of the same process. The process looks in the queue each time a message arrives until the timeout occurs.

Mapping   The abstract syntax for a fragment of Erlang that is required to present the translation is shown in Figure 3. Table 1 offers an overview of how a construct in one language relates to one in the other. We discuss the general principles behind our translation in more detail below.

Reactive classes are translated into three functions, each representing a possible behaviour of an Erlang process: 1) the process waits to get references to known rebecs, 2) the process reads the initial message from the queue and executes it, 3) the process reads messages from the queue and executes them. Once processes reach the last function they enter a loop. Erlang pseudocode for the reactive class *TicketService* in the Rebeca model in Listing 1 is shown in Listing 3.

A message server is translated into a match expression (see Figure 3), which is used inside `receive ... end`. In Listing 3, `requestTicket` is the pattern that is matched on, and the body of the message server is mapped to the corresponding expression.

Message send is implemented depending on whether `after` is used. If there is no `after`, the message is sent like a regular message using the `!` operator, as shown on line 4 in Listing

*Program ::= Function** *Function ::= v(Pattern*) → e*
   Expr ::= e_1 op_e e_2 | e(⟨e⟩) | e_1 ! e_2 | e_1 , e_2 | Pattern = e |* **case** *e* **of** *Match* **end** *|* **receive** *Match* **end**
      | **receive** *Match* **after** *Time* → *e* **end***|* **if** *⟨Match⟩***end** *| BasicValue | v | {⟨e⟩*} | [⟨e⟩*]*
  Match ::= Pattern **when** *Guard → e*
  Pattern ::= v | BasicValue | {⟨Pattern⟩} | [⟨Pattern⟩*]*   *Time ::=* int
   Value ::= BasicValue | {⟨Value⟩} | [⟨Value⟩*]*   *BasicValue ::=* atom *|* number *|* pid *|* fid
   Guard ::= g_1 op_g g_2 | BasicValue | v | g(⟨g⟩) | {⟨g⟩*} | [⟨g⟩*]*

Figure 3: Abstract syntax of a relevant subset of Erlang. Angle brackets ⟨...⟩ are used as meta parenthesis, superscript + for repetition more than once, superscript * for repetition zero or more times, whereas using ⟨...⟩ with repetition denotes a comma separated list. Identifiers *v, p* and *g* denote variable names, patterns and guards, respectively, and *e* denotes an expression. Note that {} and [] are parts of the syntax of Erlang representing tuples and lists, respectively.

Timed Rebeca		Erlang
Model	→	A set of processes
Reactive classes	→	A process whose behaviour consists of three functions
Known rebecs	→	Record of variables
State variables	→	Record of variables
Message server	→	A match in a receive expression
Local variables	→	Record of variables
Message send	→	Message send expression
Message send w/after	→	Message send expression in the timeout block of a receive with an empty pattern, the timeout block is always executed, sending the message after the specified time
Message send w/deadline	→	Message send expression with the deadline as parameter
Delay statement	→	Empty receive with a timeout
Now expression	→	System time
Assignment	→	Record update
If statement	→	If expression
Nondeterministic selection	→	Random selection in Erlang

Table 1: Structure of the mapping from Timed Rebeca to Erlang.

```
1  ticketService() ->
2    receive
3      % wait for a message with a set of known rebecs
4      {Agent} ->
5        % proceed to the next behaviour
6        ticketService(#ticketService_knownrebecs{agent=Agent})
7    end.
8  ticketService(KnownRebecs) ->
9    receive
10     % wait for the 'initial' message
11     initial ->
12       % process message 'initial' and proceed to the next behaviour
13       ticketService(KnownRebecs, #ticketService_statevars{})
14   end.
15 ticketService(KnownRebecs, StateVars) ->
16   receive
17     % wait for each message servers
18     requestTicket ->
19       % process message 'requestTicket' and loop
20       ticketService(KnownRebecs, StateVars)
21   end.
```

Listing 3: Pseudo Erlang code capturing the behaviour of the ticketService process.

```
1  Sender = self(),
2  spawn(fun() ->
3    receive after 15 ->
4      TicketService ! {{Sender, now(), inf}, requestTicket}
5    end
6  end)
```

Listing 4: Example of a message send after 15 time units in Erlang.

4. However, if the keyword `after` is present a new process is spawned which sleeps for the specified amount of time before sending the message as described before. Setting a deadline for the delivery of a message is possible by changing the value `inf`, which denotes no deadline (as shown on line 3 in Listing 4), to an absolute point in time. Messages are tagged with the time at which they were sent. For the simulation we use the system clock to find out the current time by calling the Erlang function `now()`.

Moreover, since message servers can reply to the sender of the message, we need to take care of setting the sender as part of the message as seen on line 4 in Listing 4.

As there is no pattern to match with, the *delay* statement is implemented as a receive consisting of just a timeout that makes the process wait for a certain amount of time. For example, *delay*(10) is translated to `receive after 10 ->ok end`.

The *deadline* of each message is checked right before the body of the message server is executed. The current time is compared with the deadline of the message to see if the deadline has expired and, if so, the message is purged.

Request deadline	Check issued period	Retry request period	New request period	Service time 1	Service time 2	Result
2	1	1	1	3,4	7	Not issued
2	2	1	1	4	7	Not issued
2	2	1	1	3	7	Ticket issued

Table 2: Experimental simulation results for ticket service.

5 Simulation of Timed Rebeca Using McErlang

In this section, we present experimental results for two case studies. The first case study is the ticket service model displayed in Listing 1 and the second is a model of a sensor network. In each case we run a simulation for ten times, and for each case for 30 minutes or until a runtime monitor fails, which means that an erroneous state has been reached. The simulations are run in a setting in which a time unit is 1000 ms. The experiment platform is Macbook 2.0GHz Intel Core 2 Duo - Aluminum 4GB memory Mac OS X, 10.6.6, and Erlang R13B04.

Ticket Service   The ticket service model is described in Section 3. For each simulation, we change one of the following parameters: the amount of time that is allowed to pass before a request is processed, the time that passes before agent checks if he has been issued a ticket, the amount of time that passes before agent tries the next ticket service if he did not receive a ticket, the amount of time that passes before agent restarts the ticket requests in case neither ticket service issued a ticket and two different service times, which are non-deterministically chosen as delay time in a ticket service and model the processing time for a request. Table 5 shows different settings of those parameters for which the ticket services never issue a ticket to the agent because of tight deadlines, as well as settings for which a ticket is issued during a simulation of the model.

Sensor Network   We model a simple sensor network using Timed Rebeca. (See Listing 5 in Appendix B for the complete description of the model.) A distributed sensor network is set up to monitor levels of toxic gasses. The sensor rebecs (`sensor0` and `sensor1`), announce the measured value to the admin node (`admin` rebec) in the network. If the admin node receives reports of dangerous gas levels, it immediately notifies the scientist (`scientist` rebec) on the scene about it. If the scientist does not acknowledge the notification within a given time frame, the admin node sends a request to the rescue team (`rescue` rebec) to look for the scientist. The rescue team has a limited amount of time units to reach the scientist and save him.

The rebecs `sensor0` and `sensor1` will periodically read the gas-level measurement, modelled as a non-deterministic selection between `GAS_LOW` and `GAS_HIGH`, and send their values to `admin`. The `admin` continually checks, and acts upon, the sensor values it has received. When the `admin` node receives a report of a reading that is life threatening for the `scientist` (`GAS_HIGH`), it notifies him and waits for a limited amount of time units for an acknowledgement. The `rescue` rebec represents a rescue team that is sent off, should the `scientist` not acknowledge the message from the `admin` in time. We model the response speed of the rescue team with a non-deterministic delay of 0 or 1 time units. The `admin` keeps track of the deadlines for the `scientist` and the `rescue` team as follows:

Network delay	Admin period	Sensor 0 period	Sensor 1 period	Scientist deadline	Rescue deadline	Result
1	4	2	3	2	3	Mission failed
1	4	2	3	2	4	Mission success
2	1	1	1	4	5,6,7	Mission failed
2	4	1	1	4	7	Mission success

Table 3: Experimental simulation results for sensor network.

- the `scientist` must acknowledge that he is aware of a dangerous gas-level reading before *scientistDeadline* time units have passed;

- the `rescue` team must have reached the `scientist` within *rescueDeadline* time units.

Otherwise we consider the mission failed.

The model can be parameterized over the values of network delay, `admin` sensor-read period, `sensor0` read period, `sensor1` read period, scientist reply deadline and rescue-team reply deadline, as shown in Table 5. In that table, we can see two different cases in which we go from mission failure to mission success between simulations. In the first scenario, we go from mission failure to success as we increase the rescue deadline, as expected. In the second scenario, we changed the parameters to model a faster sensor update and we observed mission failure. In this scenario, increasing the rescue deadline further (from 5 to 7) is insufficient. Upon closer inspection, we observe that our model fails to cope with the rapid sensor updates and admin responses because it enters an unstable state. The admin node initiates a new rescue mission while another is still ongoing, eventually resulting in mission failure. This reflects a design flaw in the model for frequent updates that can be solved by keeping track of an ongoing rescue mission in the model. Alternatively, increasing the value of `admin` sensor-read period above half the rescue deadline eliminates the flaw and the simulation is successful again.

6 Future Work

The work reported in this paper paves the way to several interesting avenues for future work. In particular, we have already started modelling larger real-world case studies and analyzing them using our tool. We plan to explore different approaches for model checking Timed Rebeca models. It is worth noting that the translation from Timed Rebeca to Erlang immediately opens the possibility of model checking untimed Rebeca models using McErlang. This adds yet another component to the verification toolbox for Rebeca, whose applicability needs to be analyzed via a series of benchmark examples. As mentioned in the paper, McErlang supports the notion of time only for simulation and not in model checking, and therefore cannot be used as is for model checking Timed Rebeca models. We plan to explore different ways in which McErlang can be used for model checking Timed Rebeca. One possible solution is to store the local time of each process and write a custom-made scheduler in McErlang that simulates the way the Timed Rebeca scheduler operates. The formal semantics for Timed Rebeca presented in this paper is also used in another parallel line of work [11]. The aim of that study is to map Timed Rebeca to timed automata [2] in order to use UPPAAL [24] for model checking Timed Rebeca models. The translation from Timed Rebeca to timed automata will be integrated in our tool suite. We are also working on a translation of Timed Rebeca into (Real-time) Maude. This

alternative translation would allow designers to use the analysis tools supported by Maude in the verification and validation of Timed Rebeca models. Our long-term goal is to have a tool suite for modelling, executing, simulating, and model checking asynchronous object-based systems using Timed Rebeca.

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A   Method-Execution Transition Rules

(msg) $(varname.m(\overline{v})\ after(d)\ deadline(DL), \sigma, Env, B)$

$$\xrightarrow{\tau} (\sigma, Env, \{(\sigma(varname), m(eval(\overline{v}, \sigma))), \sigma(self), \sigma(now) + d, \sigma(now) + DL)\} \cup B)$$

$(delay)$ $(delay(d), \sigma, Env, B) \xrightarrow{\tau} (\sigma[now = \sigma(now) + d], Env, B)$

$(assign)$ $(x = e, \sigma, Env, B) \xrightarrow{\tau} (\sigma[x = eval(e, \sigma)], Env, B)$

$(create)$ $(varname = new\ O(\overline{v}), \sigma, Env, B)$

$$\xrightarrow{\tau} (\sigma[varname = A], \{\sigma_A[now = \sigma(now),\ self = A]\} \cup Env, \{(A, initial(eval(\overline{v}, \sigma)), \sigma(self)), \sigma(now), +\infty)\} \cup B)$$

$(cond_1)$
$$\dfrac{eval(e, \sigma) = true \quad (S_1, \sigma, Env, B) \xrightarrow{\tau} (\sigma', Env', B')}{(if\ (e)\ then\ S_1\ else\ S_2, \sigma, Env, B) \xrightarrow{\tau} (\sigma', Env', B')}$$

$(cond_2)$
$$\dfrac{eval(e, \sigma) = false \quad (S_2, \sigma, Env, B) \xrightarrow{\tau} (\sigma', Env', B')}{(if\ (e)\ then\ S_1\ else\ S_2,\ \sigma, Env, B) \xrightarrow{\tau} (\sigma', Env', B')}$$

(seq)
$$\dfrac{(S_1, \sigma, Env, B) \xrightarrow{\tau} (\sigma', Env', B'),\ (S_2, \sigma', Env', B') \xrightarrow{\tau} (\sigma'', Env'', B'')}{(S_1; S_2, \sigma, Env, B) \xrightarrow{\tau} (\sigma'', Env'', B'')}$$

Figure 4: The Method-Execution Transitions Rules. In rule *create*, the rebec name A should not appear in the range of the environment σ. The function *eval* evaluates expressions in a given environment in the expected way. In each rule, we assume that σ is not contained in *Env*.

B   Rebeca Model for the Sensor Network

```
1   env int netDelay;
2   env int adminCheckDelay;
3   env int sensor0period;
4   env int sensor1period;
5   env int scientistDeadline;
6   env int rescueDeadline;
7
8   reactiveclass Sensor {
9       knownrebecs {
10          Admin admin;
11      }
12
13      statevars {
14          int period;
15      }
```

```
16
17      msgsrv initial(int myPeriod) {
18          period = myPeriod;
19          self.doReport();
20      }
21
22      msgsrv doReport() {
23          int value;
24          value = ?(2, 4); // 2=safe gas levels, 4=danger gas levels
25          admin.report(value) after(netDelay);
26          self.doReport() after(period);
27      }
28  }
29
30  reactiveclass Scientist {
31      knownrebecs {
32          Admin admin;
33      }
34
35      msgsrv initial() {}
36
37      msgsrv abortPlan() {
38          admin.ack() after(netDelay);
39      }
40  }
41
42  reactiveclass Rescue {
43      knownrebecs {
44          Admin admin;
45      }
46
47      msgsrv initial() {}
48
49      msgsrv go() {
50          int msgDeadline = now() + (rescueDeadline-netDelay);
51          int excessiveDelay = ?(0, 1); // unexpected obstacle might occur during rescue
52          delay(excessiveDelay);
53          admin.rescueReach() after(netDelay) deadline(msgDeadline);
54      }
55  }
56
57  reactiveclass Admin {
58      knownrebecs {
59          Sensor sensor0;
60          Sensor sensor1;
61          Scientist scientist;
62          Rescue rescue;
63      }
64
65      statevars {
66          boolean reported0;
67          boolean reported1;
68          int sensorValue0;
69          int sensorValue1;
70          boolean sensorFailure;
71          boolean scientistAck;
72          boolean scientistReached;
73          boolean scientistDead;
74      }
75
76      msgsrv initial() {
77          self.checkSensors();
78      }
79
80      msgsrv report(int value) {
```

```
81          if (sender == sensor0) {
82              reported0 = true;
83              sensorValue0 = value;
84          } else {
85              reported1 = true;
86              sensorValue1 = value;
87          }
88      }
89
90      msgsrv rescueReach() {
91          scientistReached = true;
92      }
93
94      msgsrv checkSensors() {
95          if (reported0) reported0 = false;
96          else sensorFailure = true;
97
98          if (reported1) reported1 = false;
99          else sensorFailure = true;
100
101         boolean danger = false;
102         if (sensorValue0 > 3) danger = true;
103         if (sensorValue1 > 3) danger = true;
104
105         if (danger) {
106             scientist.abortPlan() after(netDelay);
107             self.checkScientistAck() after(scientistDeadline); // deadline for the scientist to answer
108         }
109
110         self.checkSensors() after(adminCheckDelay);
111     }
112
113     msgsrv checkRescue() {
114         if (!scientistReached) {
115             scientistDead = true; // scientist is dead
116         } else {
117             scientistReached = false;
118         }
119     }
120
121     msgsrv ack() {
122         scientistAck = true;
123     }
124
125     msgsrv checkScientistAck() {
126         if (!scientistAck) {
127             rescue.go() after(netDelay);
128             self.checkRescue() after(rescueDeadline);
129         }
130         scientistAck = false;
131     }
132 }
133
134 main {
135     Sensor sensor0(admin):(sensor0period);
136     Sensor sensor1(admin):(sensor1period);
137     Scientist scientist(admin):();
138     Rescue rescue(admin):();
139     Admin admin(sensor0, sensor1, scientist, rescue):();
140 }
```

Listing 5: A Timed Rebeca model of the sensor network example