

Electronic Notes in Theoretical Computer Science 258 (2009) 63–77

[www.elsevier.com/locate/entcs](http://www.elsevier.com/locate/entcs)

The tccp Interpreter

Alexei Lescaylle[1](#_bookmark0)*,*[2](#_bookmark0) Alicia Villanueva[3](#_bookmark0)

*DSIC, Universidad Polit´ecnica de Valencia Valencia, Spain*

**Abstract**

The *Timed Concurrent Constraint* language (tccp in short) is a declarative language inspired by some formalisms specially developed to deal with concurrent and reactive systems. It is defined as a timed extension of the Saraswat’s *Concurrent Constraint Paradigm* (ccp in short) which makes the new language suitable for modeling reactive systems. The computational model of ccp is based on agents generating (*telling* ) and checking (*asking* ) partial information (*constraints*) on a global *store* (a conjunction of constraints). tccp inherits the main characteristics of ccp: it is parametric

w.r.t. a constraint system and non-deterministic. This work presents the tccpInterpreter system, which is the result of implementing the tccp language in Maude. Maude has been shown to be well suited for the task of prototyping the semantics of programming languages. Our tccpInterpreter parses a given program and simulates its behavior, also allowing us to reuse the Maude features to execute and analyze tccp programs.

*Keywords:* Tool demonstration, Timed Concurrent Constraint Language, Maude

# Introduction

The Saraswat’s *Concurrent Constraint Programming* paradigm, ccp in short [[14](#_bookmark21)], is a simple but powerful model for expressing concurrent systems. The computational model is based on agents interacting among them by adding and consulting partial information (constraints) in a global *store*. ccp replaces the classical notion of store as a collection of valuations of variables by the

1 This work has been supported by the Spanish MEC under grant TIN2007-68093-C02-02, by the Generalitat Valenciana under grant GV/2009/024 and by the Universidad Polit´ecnica de Valencia, under grant PAID-06-07 (TACPAS).

2 Email: [alescaylle@dsic.upv.es](mailto:alescaylle@dsic.upv.es)

3 Email: [villanue@dsic.upv.es](mailto:villanue@dsic.upv.es)

1571-0661© 2009 Elsevier B.V. Open access under [CC BY-NC-ND license.](http://creativecommons.org/licenses/by-nc-nd/3.0/)

doi:10.1016/j.entcs.2009.12.005

notion of store as a conjunction of constraints. The *Timed Concurrent Con- straint* language, tccp in short [[5](#_bookmark15)], extends the ccp paradigm with a notion of time that makes the language suitable for modeling reactive systems [[8](#_bookmark18)], namely systems which maintain an ongoing information exchange with their environment at run-time.

The tccp language inherits some significant characteristics from ccp: it is parametric w.r.t. a given constraint system, non-deterministic, and the stored information grows monotonically. The underlying constraint system specifies which kind of constraints the system will be able to handle, and the relation among them. The non-deterministic behavior allows us to have more compact and precise specifications for large systems. Finally, the monotonic behavior of the store implies that information cannot be canceled, thus it is necessary to use *streams* to model the classical evolution of variable values.

The temporal model introduced in tccp is based on a global clock that synchronizes the execution. The *agent-based* model provides an intuitive way to specify reactive and embedded systems. Thanks to the new features (w.r.t. ccp), the language is able to capture typical behaviors of reactive systems such as *time-outs*, *time-delays* or *watchdogs*. Furthermore, since time is embedded in the semantics of the language, it is possible to naturally use the (constrained version of) Linear Temporal Logic (LTL) proposed in [[5](#_bookmark15)] to specify and model check properties of tccp programs [[3](#_bookmark13),[2](#_bookmark12),[6](#_bookmark16)].

The rewriting logic-based and high-performance reflective specification lan- guage Maude [[4](#_bookmark14),[1](#_bookmark11)] has been proposed for the task of building and analyzing a wide range of applications. In particular, rewriting logic [[12](#_bookmark22)] can deal with state and concurrent computations and has been used as a semantic framework for giving executable semantics to (concurrent) languages and models. Maude supports structured theory specifications, algebraic data types and function specification in rich equational logics. We assume that the reader has a basic knowledge of Maude [4](#_bookmark1) .

As an example of the use of Maude as a semantic framework to provide executable semantics, we find in [[7](#_bookmark17)] JavaFAN (Java Formal ANalyzer), which is a tool that formally specifies the Java semantics in Maude. In [[16](#_bookmark26)] it is presented an interpreter of LOTOS based on the symbolic semantics for Full LOTOS [[11](#_bookmark23)]. In [[17](#_bookmark27)], the operational semantics of CCS [[13](#_bookmark24)] is implemented in Maude. CCS is in some sense similar to tccp. For example, operators like Nil or Choice are present in both languages. However, there are also important differences: in tccp the model for concurrency is based on maximal parallelism whereas in CCS it is used the interleaving model. In tccp, agents interact by using a global store (adding or consulting information) whereas in CCS, a

4 For more detailed documentation about Maude, the interested reader can consult [[4](#_bookmark14),[1](#_bookmark11)].

process may use communication ports to interact with other processes.

In this work we present the tccpInterpreter system: an interpreter for the tccp language. The tool is the implementation of the tccp formalism in Maude. The interpreter parses the tccp program, executes it (simulating its behavior), and also some analysis of the tccp program can be run. The analysis is carried out by using the Maude’s *search* command which explores all the possible computations of a program, looking for safety violations when desiderated. Finally, it is important to note that tccpInterpreter incorporates some notions from [[2](#_bookmark12)] that were not present in the original definition of the language but that make the tccp framework more flexible.

To our knowledge, there is just an implementation of tccp. In [[15](#_bookmark25)] it was presented a prototype developed in the Mozart-Oz language. Mozart-Oz [[9](#_bookmark19)] is a multi-paradigm language allowing multi-threaded higher order programs to be directly executed in a distributed open system. However, the proposal is not publicly available and does not support the new features of tccp presented during the last years.

This work is organized as follows. In Section [2](#_bookmark2) we present the basic notions of the tccp language. Then, in Section [3](#_bookmark4) we partially describe how the syntax and operational semantics of tccp have been implemented in Maude. A model for a specific constraint system is shown in Section [4](#_bookmark6). Section [5](#_bookmark7) is devoted to show the functionality of the tool by using an illustrative example and, finally, in Section [6](#_bookmark10) we conclude and give some directions for future work.

# The tccp language

Let us first recall the syntax of the agents of the tccp language. A tccp program *P* is of the form *D.A* where *D* is a set of declarations of the form p(*x*) :*−B* and *A* is an agent that initiates the execution. We assume that *c* and *ci* are finite constraints (i.e., elements) of the underlying constraint system. Then, a tccp agent is defined as follows:

*A, B* ::= skip *|* tell(*c*) *|* Σ*n* ask(*ci*) *→ Ai |* now *c* then *A* else *B | A||B | ∃xA |* p(*x*)

*i*=1

In brief, the skip agent does nothing. tell(*c*) adds the constraint *c* to the

store. The choice agent Σ*n* ask(*ci*) *→ Ai* models the non-determinism: it

*i*=1

checks whether the store satisfies the constraints *ci* and non-deterministically

executes one of the agents *Ai* whose condition *ci* is satisfied. In case no condi- tion *ci* is entailed, the choice agent *suspends* (it will be executed again in the following time instant). The conditional agent now *c* then *A* else *B* executes agent *A* if the store satisfies *c*, otherwise executes *B*. Note that due to the partial nature of the stored information, the fact that *c* is not satisfied does

not imply that *¬c* is satisfied. *A * *B* executes the two agents *A* and *B* in parallel following the *maximal parallelism* model. The *∃xA* agent is used to define the variable *x* local to the process *A*. Finally, p(*x*) is the procedure call agent where *x* denotes the set of parameters of the process p.

The notion of time is modeled in the language following the idea that updates and consults to the store takes one time unit. Therefore, only the tell, choice and procedure call agents consume time. The rest of agents are considered instantaneous.

Similarly to ccp, the store in the original model of tccp behaves monotoni- cally. Thus, it is not possible to change the value of a given variable along the time. This problem can be solved by using *streams*. For instance, we write *X* = [1*|Z*] to denote a variable *X* recording the current value 1. The variable *Z* represents the future values of *X*. To ease the tasks related to streams manipulation, we use the modified computation model for tccp presented in

[[2](#_bookmark12)] where the notion of global store was replaced by the notion of *structured store*. A structured store consists of a sequence of stores where each store of the sequence contains only the constraints added in the corresponding time instant.

tccpInterpreter considers three new agents introduced in [[10](#_bookmark20)] to deal in a more compact way with some common behaviors regarding streams. The ask-tell(*S, V* ) agent consults the current value of the stream *S* and updates the store by instantiating the fresh variable *V* to such value. The update(*S, V, T* ) agent inserts the value of the variable *V* in the stream *S*. *T* represents the future values of *S*. Finally, the assign(*S, Vf , Va*) agent consults whether the value of *Vf* can be recovered from (any of the values stored in) the stream *S*; in that case, it instantiates *Va* to the recovered value.

We can see in Figure [1](#_bookmark3) the operational semantics of the language borrowed from [[2](#_bookmark12)] that it is slightly different from the original model in [[5](#_bookmark15)] due to the new computational model based on structured stores. It is given by means of a transition relation between configurations, which are composed by an agent

and the store *st* (at the current time instant *t*

*.* o and *⊃*˙

are

). The symbols =,

related to the operations of consulting the last value and tail of streams and the containment of a value in a stream. Finally, functions *free* and *len* check whether a variable is instantiated, and compute the length of a given stream, respectively.

Let us describe some of these semantic rules. The first rule **R1** specifies the evolution of the tell agent: it reaches a skip agent in the following time instant with the given store *st* augmented with the constraint *c*. Rule **R2** states that *Aj* is executed in the following time unit whenever *st* entails the condition *cj*. Regarding the conditional agent, **R3** models the case when the

|  |  |  |
| --- | --- | --- |
| **R12** | *⟨*update(*S, Vi, Ct*)*, st⟩t −→ ⟨*skip*, st Ht*+1 *S* = [*Vi|Ct*]*⟩t*+1 | *len*(*S, st, t*) *>* 0  if *st |*=*t free*(*S*),*free*(*Ct*) |
| **R13** | *⟨*update(*S, Vi, Ct*)*, st⟩t −→ ⟨*skip*, st Ht*+1 *TC* = [*Vi|Ct*]*⟩t*+1 | if *st |*=*t S* o *TC* ,*free*(*Ct*),  *len*(*S, st, t*) *>* 0 |
| **R14** | *⟨*assign(*S, Vf , Va*)*, st⟩t −→ ⟨*skip*, st Ht*+1 *Va* = *Vf ⟩t*+1 | if *st |*=*t S⊃*˙ *Vf* ,*free*(*Va*) |

Fig. 1. Operational semantics of the tccp language.



**R1** *⟨*tell(*c*)*, st⟩t −→ ⟨*skip*, st Ht*+1 *c⟩t*+1

**R2**

*⟨*P*n*

*i*=0

**R3**

ask(*ci*) *→ Ai, st⟩t −→ ⟨Aj, st⟩t*+1

*⟨A, st⟩t −→ ⟨A', st'⟩t*+1

if 0 *≤ j ≤ n*,*st ▶t cj*

**R4**

**R5**

*⟨*now *c* then *A* else *B, st⟩t −→ ⟨A', st'⟩t*+1

*⟨B, st⟩t −→ ⟨B', st'⟩t*+1

*⟨*now *c* then *A* else *B, st⟩t −→ ⟨B', st'⟩t*+1

*⟨A, st⟩t /−→*

*⟨*now *c* then *A* else *B, st⟩t −→ ⟨A, st⟩t*+1

*⟨B, st⟩t /−→*

*⟨*now *c* then *A* else *B, st⟩t −→ ⟨B, st⟩t*+1

*⟨A, st⟩t −→ ⟨A', st'⟩t*+1*, ⟨B, st⟩t −→ ⟨B', st''⟩t*+1

if *st ▶t c*

if *st /▶t c*

if *st ▶t c*

**R6**

if *st /▶t c*

**R7**

*⟨A*

*B, st⟩t −→ ⟨A' B', st' H st''⟩t*+1

**R8**

*⟨A, st⟩t −→ ⟨A', st'⟩t*+1*, ⟨B, st⟩t /−→*

*⟨A*

*B, st⟩t −→ ⟨A' B, st'⟩t*+1

*' '*

**R9** *⟨A, st* 1 *H ∃x st* 2*⟩t −→ ⟨A , st ⟩t*+1

*⟨∃st*1 *x A, st* 2*⟩t −→ ⟨∃st' x A', st* 2 *H ∃x st'⟩t*+1

**R10** *⟨*p(*x*)*, st⟩t −→ ⟨A, st⟩t*+1

if p(*x*): *−A ∈ D*

**R11** *⟨*ask-tell(*S, Cv* )*, st⟩t −→ ⟨*skip*, st Ht*+1 *Cv* = *VC⟩t*+1

if *st |*= *S* = *V* ,*free*(*C* ),

*t*

*.*

*C*

*v*

condition holds. In case that the agent *A* with the current store *st* can evolve in the agent *A'* and a new store *st'*, then *A'* is executed in the following time instant. **R7** models the evolution of the  agent: in case that *A* with store *st* is able to evolve to the agent *A'* with *st'*, and also *B* with store *st* is able to evolve into the agent *B'* with *st''*, then *A'||B'* is executed in the following time instant with *st'* augmented with *st''*.

# The interpreter implementation

The tccpInterpreter system is the result of the implementation in Maude of the tccp formalism, i.e., the language operational semantics plus a specific con- straint solver. The tool takes as input the specification of a tccp program and simulates its behavior following the semantics of the language. tccpInterpreter

consists of approximately 1080 lines of code divided in six Maude modules. Each module models one or more of the entities of tccp: agents, constraints, programs, the store, the underlying constraint system, the operational seman- tics, etc. Maude allows us to implement a constraint solver for the language or to use an existing one to handle constraints. [5](#_bookmark5)

* 1. *Syntactic objects*

The representation of the syntax of tccp in Maude is quite intuitive for all tccp constructs. Agents are defined to be terms of *sort* TccpAgent. For instance, the tell agent is encoded by using a Maude constructor symbol with identifier tell followed by the given constraint (a term of sort TccpConstraint):

op tell : TccpConstraint -> TccpAgent .

The conditional agent is encoded by defining the identifier now followed by a boolean constraint (term of sort TccpBoolean), the then block which contains an agent, and the else block with another agent.

op now then else : TccpBoolean TccpAgent TccpAgent -> TccpAgent .

The choice agent is encoded by using two Maude constructor symbols. The first one models a single branch of a choice: the identifier ask is followed by a Boolean constraint, the arrow -> and an agent. The second one models the composition of two or more branches:

op ask -> : TccpBoolean TccpAgent -> TccpChoice .

op + : TccpChoice TccpChoice -> TccpChoice [assoc comm] .

Note that the operator + is labeled with the attributes assoc and comm since it is associative and commutative.

The parallel agent is encoded by using the constructor symbol || composed by two agents.

op || : TccpAgent TccpAgent -> TccpAgent [assoc] .

The rest of tccp agents are encoded similarly. The system models all the agents appearing in Figure [1](#_bookmark3), including those introduced in [[10](#_bookmark20)].

* 1. *The Operational Semantics*

The operational semantics of tccp are encoded in Maude as transitions over configurations by means of Maude rules. For readability, each rule is la- beled with an identifier. One configuration (of sort TccpConfig) contains

5 It is possible to interact with Maude from other platforms, for example from Java.

a triple with the set of declarations of the given tccp program (a term of sort TccpDeclarationSet), the agent to be executed (a term of sort TccpAgent) and the current store (a term of sort TccpStructuredStore):

op *< , , >* : TccpDeclarationSet TccpAgent TccpStructuredStore -> TccpConfig .

The (structured) store at a given time instant is encoded as a store (a term of sort TccpStore) and a natural number between brackets denoting the current time instant:

op *{ }* : TccpStore Nat -> TccpStructuredStore .

In the following, we show how some of the semantics’ rules are specified in Maude. Let us start by describing the case for the conditional agent, modeled by the Maude conditional rules now-true and now-false. Maude conditional rules are of the form crl *T* => *T '* if *C* and state that one term *T* rewrites (=>) to a second term *T '* whenever the condition *C* is satisfied. Then, the now-true rule shown below is executed just when its condition holds. In other words:

* + 1. the store TpSt represents all the information stored in SS*{*t*}* up to the current time instant,
    2. TpSt satisfies the constraint CtBl of the conditional tccp agent. This is checked by means of the function consultTccpStore (TpSt , CtBl), and
    3. Ag1’ is the result of executing Ag1 with the current store.

crl [now-true]: *<* DcSt , now (CtBl) then Ag1 else Ag2 , SS*{*t*} >* =*>*

*<* DcSt , Ag1’ , SS1*{*k*} >*

if TpSt := returnGlobalStoreFromStructuredStoreList (SS*{*t*}*) *∧*

consultTccpStore (TpSt , CtBl) == ctrue *∧*

*<* DcSt , Ag1 , SS*{*t*} >* =*> <* DcSt , Ag1’ , SS1*{*k*} >* .

consultTccpStore (TpSt , CtBl) gets as input the store TpSt and the boolean constraint CtBl and returns ctrue when the store entails the given constraint or cfalse otherwise. When the condition holds, we reach the con- figuration *<* DcSt , Ag1’ , SS1*{*k*}* resulting of executing the agent in the then branch of the conditional agent. The now-false rule is defined similarly:

crl [now-false]: *<* DcSt , now (CtBl) then Ag1 else Ag2 , SS*{*t*} >* =*>*

*<* DcSt , Ag2’ , SS2*{*k*} >*

if TpSt := returnGlobalStoreFromStructuredStoreList (SS*{*t*}*) *∧*

consultTccpStore (TpSt , CtBl) == cfalse *∧*

*<* DcSt , Ag2 , SS*{*t*} >* =*> <* DcSt , Ag2’ , SS2*{*k*} >* .

The following code excerpt describes the rules modeling the semantics of the choice agent. The rule ask-true specifies the case when a choice agent with a single branch can be executed. In this case, the agent ask(CtBl) -> Ag evolves to a configuration containing the original declarations set DcSt, the agent to be executed Ag and the structured store resulting from updating the given store SS*{*t*}* with the empty store (strue). The symbol => is also used to incrementally identify the components of a structured store. The conditional rule states that the agent is executed only when the store TpSt satisfies the constraint CtBl of the agent, checked by means of consultTccpStore (TpSt

, CtBl) == ctrue.

crl [ask-true]: *<* DcSt , ask(CtBl) -> Ag , SS*{*t*} >* =*>*

*<* DcSt , Ag ,(SS*{*t*}* => strue *{*t + 1*}*)*>*

if TpSt := returnGlobalStoreFromStructuredStoreList (SS*{*t*}*) *∧*

consultTccpStore (TpSt , CtBl) == ctrue .

The conditional rule choice-true models the case when the choice agent has more than one branch and one of them can be executed. Since the operator

+ is associative and commutative, we have to describe just the first branch (ask(CtBl) -> Ag) of the given agent:

crl [choice-true]: *<* DcSt , ((ask(CtBl) -> Ag) + AgCh) , SS*{*t*} >*

=*> <* DcSt , Ag , (SS*{*t*}* => strue *{*t + 1*}*) *>*

if TpSt := returnGlobalStoreFromStructuredStoreList (SS*{*t*}*) *∧*

consultTccpStore (TpSt , CtBl) == ctrue .

Finally, the choice-false rule models the case when the choice agent sus- pends, meaning that none of the constraints appearing in the choice agent AgChS is satisfied. In this case, the agent AgChS is executed in the following time instant:

crl [choice-false] : *<* DcSt , AgChS , SS*{*t*} >* =*>*

*<* DcSt , AgChS , (SS*{*t*}* => strue *{*t + 1*}*) *>*

if TpSt := returnGlobalStoreFromStructuredStoreList (SS*{*t*}*) *∧*

consultTccpStore (TpSt , AgChS) == cfalse .

The parallel agent is specified as the following conditional rule where it is reached the configuration resulting of executing, at the same time, the agents Ag1 and Ag2. The execution of Ag1 produces Ag1’ and the structured store SS1*{*k*}*, whereas the execution of Ag2 produces Ag2’ and the structured store SS2*{*k*}*. Then, the resulting configuration contains the parallel composition of both Ag1’ and Ag2’, and the structured store resulting of joining the struc- tured stores: (SS1 *∧* SS2)*{*k*}*).

crl [parallel]: *<* DcSt , Ag1 || Ag2 , SS*{*t*} >* =*>*

*<* DcSt , Ag1’ || Ag2’, (SS1 *∧* SS2)*{*k*} >*

if *<* DcSt , Ag1 , SS*{*t*} >* =*> <* DcSt , Ag1’ , SS1*{*k*} > ∧*

*<* DcSt , Ag2 , SS*{*t*} >* =*> <* DcSt , Ag2’ , SS2*{*k*} >* .

The remaining rules are defined similarly.

# The underlying constraint solver

Other important point in the tccp framework is the interaction with the un- derlying constraint solver. Typically, the constraint solver must be able of solving arithmetic and boolean constraints, and to perform some operations with streams. These goals can be achieved in an elegant way implementing the constraint system in Maude. Once defined the types of the expressions and the syntax of the operators needed to handle constraints, we specify the rules describing the evolution of each possible combination, thus the satisfaction relation.

The sort TccpArithmetic is used to represent the data types for arithmetic operations:

subsorts Float TccpVariable *<* TccpArithmetic .

Currently, TccpArithmetic includes floating-point numbers and variables. The following operators represent the *sum*, *rest*, *multiplication* and *division* of two arithmetic terms (TccpArithmetic) returning another arithmetic term, respectively:

ops +’ -’ : TccpArithmetic TccpArithmetic ->

TccpArithmetic [prec 33 gather (E e)] . ops \*’ /’ : TccpArithmetic TccpArithmetic ->

TccpArithmetic [prec 31 gather (E e)] .

The attribute prec sets the precedence of the operators given as a natural number: a lower value indicates a tighter binding and the attribute gather (E e) restricts the precedence of TccpArithmetic terms that are allowed as arguments. Both mechanisms avoid possible ambiguities arising when parsing

TccpArithmetic terms.

The operation semantics for the constraint system is modeled by using Maude equations in the module TCCP-STORE. For example, we define a Maude equation to add two numbers, another equation to add a variable (of sort TccpVariable) whose value must be recovered from the current store and a number, etc. We have an operator evalTccpArithmetic that, given a TccpArithmetic expression and the current store, returns the expected re- sult. In case that the expression cannot be evaluated, it returns the original expression. The following equation specifies the simple case when, given the store TpSt, we add two floating numbers: Ft1 and Ft2.

eq evalTccpArithmetic (Ft1 +’ Ft2 , TpSt) = Ft1 + Ft2 .

Below we show the case for the sum of two variables TpVar1 and TpVar2 given the store TpSt. By means of the operator evalArithmeticVariableInStore we can recover from the store the value of TpVar1 and TpVar2. In case that both values are floating numbers, evalArithmetic returns the sum of both:

ceq evalTccpArithmetic (TpVar1 +’ TpVar2 , TpSt) = Ft1 + Ft1 if Ft1 := evalArithmeticVariableInStore (TpVar1 , TpSt) *∧*

Ft1 =/= noIsFloat *∧*

Ft2 := evalArithmeticVariableInStore (TpVar2 , TpSt) *∧*

Ft2 =/= noIsFloat .

When a computation cannot be taken, then the input expression is returned:

ceq evalTccpArithmetic (TpAr , TpSt) = TpAr [owise] .

The expression TccpBoolean is used to represent the data types needed to handle boolean constraints:

subsorts TccpExpression TccpArithmetic *<* AuxConstraint . subsorts Float TccpConstant TccpVariable *<* TccpExpression . subsorts TccpTerm TccpStream *<* TccpExpression .

ops *<*’ *>*’ ==’ !=’ *<*=’ *>*=’ : AuxConstraint AuxConstraint ->

TccpBoolean [prec 37] .

op and’ : TccpBoolean TccpBoolean -> TccpBoolean [prec 55 assoc comm] . op or’ : TccpBoolean TccpBoolean -> TccpBoolean [prec 59 assoc comm] . op not’ ( ) : TccpBoolean -> TccpBoolean [prec 53] .

We can consult whether two numbers (Float) are equal, whether one is smaller than the other, one variable (TccpVariable) is greater or equal to another (their values are recovered from the store), etc. Regarding streams, we can recover the values stored in a stream, the current tail, and also the current value of a stream (the last added value).

# Running the interpreter

The interface of our tool is guided in a Maude console. To run the tool, we have to use the Maude command *load* file-name:

Maude*>* load *.. .*/tccpInterpreter.maude

Once the interpreter is loaded, we can use the Maude commands to invoke actions. For example, we can use the command *red* expression to parse or to identify an expression (an entity of the language). The command checks the given expression and returns the type or the sort associated to it. In other words, it tries to reduce the given expression following the specified grammar. The following example shows the output of Maude when reducing a tccp agent.

Maude*>* red tell (’X :=’ 1.) .

reduce in TCCP-INTERPRETER : tell(’X :=’ 1.0) . rewrites: 5 in 0ms cpu (0ms real) (*∼* rewrites/second) result TccpAgent: tell(’X :=’ 1.0)

TCCP-INTERPRETER is the main module of the tccpInterpreter. The example shows that the given expression is an agent of the language.

We can also use the command *rew* expression to explore the possible behavior of a tccp program. For example:

Maude*>* rew *<* DcSt , tell(’C :=’ 2.) , (strue *{*0*}*) *>* .

rewrite in TCCP-INTERPRETER : *<* DcSt,tell(’C :=’ 2.0),strue*{*0*} >* . rewrites: 16 in 0ms cpu (0ms real) (*∼* rewrites/second)

result TccpConfig: *<* DcSt,skip,(strue*{*0*}*) => (’C :=’ 2.0)*{*1*} >*

The execution of the given tell agent creates a new structured store with the information (’C := 2.0)*{*1*}* that is added to the initial store strue*{*0*}*.

Finally, the *search* command allows us to explore the reachable state space in different ways. We write:

search Term1 =*>*\* Term2 .

to carry out the proof from the term Term1 consisting of none, one, or more steps (=*>*\*) to the pattern Term2 to be reached.

* 1. *Illustrative example*

Here we describe a more elaborated example of an interaction with the tc- cpInterpreter system. In Figure [2](#_bookmark8) we show the specification in tccp of a part of a microwave oven controller that we have borrowed from [[6](#_bookmark16)]. To make the description clearer we show a labeled version of the declaration. Labels appear within braces *{ }*:

*{D} {*ld*}* microwave error(Door,Button,Error) :-

*{*le0*}∃* D,B,E (*{*lp1*}*(*{*lt2*}*tell(Error=[ |E])



*{*lp3*}*(*{*lt4*}*tell(Door=[ |D])

*{*lp5*}*(*{*lt6*}*tell(Button=[ |B])

*{*lp7*}*(*{*ln8*}*now(Door=[open|D] *∧* Button=[on|B]) then

*{*lp9*}*(*{*le10*}∃*E1(*{*lt11*}*tell(E=[yes|E1])) 

*{*le12*}∃*B1(*{*lt13*}*tell(B=[off|B1])))

else*{*le14*}∃*E1(*{*lt15*}*tell(E=[no|E1])) 

*{*lc16*}*microwave error(D,B,E))))).

Fig. 2. The microwave error declaration in tccp.

The declaration *D* models the process of detecting whether the door of the microwave is open at the same time that it is turned-on. This situation is controlled by the conditional agent in ln8. In case the condition holds, the process forces (with the tell agent in lt13) the microwave to be turned-off in the following time instant. Moreover, an error signal must be emitted (agent lt11). If the condition does not hold, then the system emits (via another tell agent lt15) a signal of *no error* that will be available in the store at the following time instant. These signals may be captured by other processes, thus it can be seen that the store allows the synchronization of processes. Finally, the procedure call agent microwave error(D,B,E) models the recursion of the system.

By using the following command in the Maude console, once loaded the

tccpInterpreter, the system simulates the behavior of the given declaration *D* [6](#_bookmark9) .

Maude*>* search *< D*,’microwave error ([’open|’ ],[’on|’ ],[’no|’ ]), (strue*{*0*}*) *>* =*>*\* *< D*,Ag,St *>* .

The first term specifies the configuration, composed by the declaration *D*, the procedure call agent ’microwave error ([’open|’ ],[’on|’ ],[’no|’ ]) and the empty store at time instant 0 (strue*{*0*}*). The proof consists in reaching the second term that specifies the configuration containing *D*, an agent Ag and the structure store St. By using the non-instantiated variables Ag and St we can simulate the behavior of the given procedure call agent at each time unit. Note that we can perform a different proof by using a specific agent or a specific structured store in the second term.

The recursive procedure call agent (lc16) causes the system not to end, but this is the expected behavior in the tccp execution model. Therefore, we have to deal with infinite sets of states. To make the execution finite, we can use the Maude debugging feature [[4](#_bookmark14)] to capture each step of the computation, or to use a ceiling of time-units in the evolution of a tccp specification.

In the following we show a part of the Maude output for the execution

6 For readability, we use *D* instead of the whole code of the declaration.

of the command described previously. It shows the resulting store at time instant 2. In the execution graph, at time instant 0 the store is empty. At time instant 1, the store contains the information resulting by the procedure call in the first term, where the parameters of the call are instantiated. Finally, at time instant 2 the store contains the information added by the tell agents lt11 and lt13 (the constraint of the conditional agent ln8 is satisfied), and the information added by the second procedure call lc16:

(strue *{*0*}*) =>

(((’Button :=’ [’on *|* ’TailStr’]) (’Door :=’ [’open *|* ’TailStr])

(’Error :=’ [’no *|* ’TailStr’’])) *{*1*}*) =>

((’B :=’ [’off *|* ’B1]) (’Button’ :=’ ’B) (’E :=’ [’yes *|* ’E1])

(’Error’ :=’ ’E) (’TailStr :=’ ’D) (’TailStr’ :=’ ’B)

(’Door’ :=’ ’D) (’TailStr’’ :=’ ’E)) *{*2*}* => *...*

The system returns the final configuration reached by the given specification when it ends. The most relevant information in the configuration is the re- sulting structured store which can be used later to reason with the given specifications.

# Conclusions and Future Work

We have presented the tccpInterpreter system, an interpreter for the tccp lan- guage that, given the specification of a tccp program, is able to simulate the corresponding behavior of such program following the semantics of the language. It has been implemented in Maude, an executable rewriting logic language that allows a precise specification of tccp describing, in a intuitive way, all the entities of the language such as the underlying constraint system, agents, and its operational semantics.

We have presented how the Maude system can be used as a semantic frame- work and metalanguage to build an entire environment and mechanisms for the execution of the formal specification language tccp. Maude leads to an per- spicuous formulation in the task of specifying transition systems. It presents a rich notation supporting formal specification and implementation of concur- rent systems. In this paper, we demonstrate the feasibility and the interest of formalizing the behavior of tccp with the Maude language.

We have described the functionality of tccpInterpreter by using a prac- tical example. The tool is publicly available at the url [http://www.](http://www.dsic.upv.es/~villanue/tccpInterpreter/) [dsic.upv.es/~villanue/tccpInterpreter/](http://www.dsic.upv.es/~villanue/tccpInterpreter/) and [http://www.dsic.upv.](http://www.dsic.upv.es/~alescaylle/tccp.html) [es/~alescaylle/tccp.html](http://www.dsic.upv.es/~alescaylle/tccp.html). To our knowledge, there was no adequate and public implementation of tccp so far.

One of the important advantages of this implementation is that once we have the tccp language encoded in Maude, we can use the Maude related- tools to reason about tccp programs, for example, for model checking. This interpreter allows us to explore the particular features of tccp and its behavior (maximal parallelism and the underlying constraint system).

We plan to extend our tool in several ways. To improve the interface of the system we plan to construct a graphical web interface. We plan to study both, how to carry out the implementation of the model-checking algorithm pro- posed in [[6](#_bookmark16)] for tccp programs, and how to adjust the Maude’s model-checker to verify tccp programs. In this way we aim at comparing both approaches to determine which one is the most appropriate in terms of efficiency.

# Acknowledgement

We gratefully thank Pedro Ojeda For´es for his unconditional help in the im- plementation of the tccpInterpreter system.

# References

1. Maude Web Site. <http://maude.csl.sri.com/>, 2009.
2. M. Alpuente, M. M. Gallardo, Ernesto Pimentel, and A. Villanueva. Verifying Real-Time Properties of tccp Programs. *Journal of Universal Computer Science*, 12(11):1551–1573, 2006.
3. M. Alpuente, M.M. Gallardo, E. Pimentel, and A. Villanueva. A semantic framework for the abstract model checking of tccp programs. *Theoretical Computer Science*, 346(1):58–95, 2005.
4. M. Clavel, F. Dur´an, S. Eker, P. Lincoln, N. Mart´ı-Oliet, J. Meseguer, and C. L. Talcott. *All About Maude - A High-Performance Logical Framework, How to Specify, Program and Verify* *Systems in Rewriting Logic*, volume 4350 of *Lecture Notes in Computer Science*. Springer, 2007.
5. F. S. de Boer, M. Gabbrielli, and M. C. Meo. A Temporal Logic for Reasoning about Timed Concurrent Constraint Programs. In *TIME ’01: Proceedings of the Eighth International Symposium on Temporal Representation and Reasoning (TIME’01)*, page 227, Washington, DC, USA, 2001. IEEE Computer Society.
6. M. Falaschi and A. Villanueva. Automatic Verification of Timed Concurrent Constraint Programs. *Theory and Practice of Logic Programming*, 6(3):265–300, May 2006.
7. A. Farzan, F. Cheng, J. Meseguer, and G. Rosu. Formal analysis of Java programs in JavaFAN. In *Proceedings of Computer-aided Veriﬁcation (CAV’04)*, volume 3114 of *LNCS*, pages 501 – 505, 2004.
8. D. Harel and A. Pnueli. On the development of reactive systems. pages 477–498, 1985.
9. S. Haridi, P. Van Roy, P. Brand, and C. Schulte. Programming Languages for Distributed Applications. *New Generation Computing*, 16(3):223–261, 1998.
10. A. Lescaylle and A. Villanueva. Verification and Simulation of protocols in the declarative paradigm. Technical report, DSIC, Univeridad Polit´ecnica de Valencia, 2008. Available at <http://www.dsic.upv.es/~alescaylle/files/dea-08.pdf>.
11. L. Logrippo, M. Faci, and M. Haj-Hussein. An introduction to LOTOS: learning by examples.

*Comput. Netw. ISDN Syst.*, 23(5):325–342, 1992.

1. N. Mart´ı-Oliet and J. Meseguer. Rewriting logic as a logical and semantic framework. 4(1):1– 36, January 2004.
2. R. Milner. *Communication and concurrency*. Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1989.
3. V. A. Saraswat, R. Jagadeesan, and V. Gupta. Foundations of Timed Concurrent Constraint Programming. In *Proc. of LICS’94*. IEEE CS, 1994.
4. T. Sj¨oland, E. Klintskog, and S. Haridi. An interpreter for Timed Concurrent Constraints in Mozart (extended abstract). 2001.
5. A. Verdejo. A tool for Full LOTOS in Maude. Technical Report 123-02, Dpto. Sistemas Informaticos y Programacion, Universidad Complutense de Madrid, 2002.
6. A. Verdejo and N. Marti-Oliet. Implementing CCS in Maude 2. Technical report, 2002.