

# Model Checking Communicative Agent-Based Systems

Jamal Bentahar<sup>1</sup> and John-Jules Meyer<sup>2</sup>

<sup>1</sup> Concordia University, Concordia Institute for Information Systems Engineering,  
Montreal, QC, Canada

<sup>2</sup> Utrecht University, Department of Information & Computer Science, The Netherlands

**Abstract.** Model checking is a formal technique used to verify communication protocols against given properties. In this paper, we address the problem of verifying systems designed as a set of autonomous interacting agents using such a technique. These software agents are equipped with knowledge and beliefs and interact with each other according to protocols governed by a set of logical rules. We present a tableau-based model checking algorithm for these systems and provide the termination and complexity results.

**Keywords.** Multi-agent systems, model checking, temporal logic

## Introduction

Although formal verification methods are not yet widely used to check large and complex systems, they are useful for the verification of some properties in relatively small systems involving concurrency and communication protocols. *Deadlock* (two or more processes are each waiting for another to release a resource), *safety* (same bad situation may never occur), and *reachability* (some particular situation can be reached) are examples of such properties. Formal methods offer a potential to obtain an early integration of verification in the design process, and to reduce the verification time. However, they are only applicable for finite state systems and they generally operate on system models and not on the actual system.

We distinguish two main formal verification approaches: proof-based approaches and model-based approaches. In the proof-based approaches, the system description is a set of logical formulae  $\Gamma$  and the specification is another formula  $\phi$ . The verification method consists of trying to find a proof that  $\Gamma \vdash \phi$ . This typically requires guidance and expertise from the user in order to identify suitable lemmas and auxiliary assertions. In the model-based approaches, also called *model checking*, the system (the protocol) is represented by a finite model  $M$  modeled as a *Kripke structure* using an appropriate logic. The specification is again represented by a formula  $\phi$  expressed in the same logic, and the verification method consists of computing whether the model  $M$  satisfies  $\phi$  or not ( $M \models \phi$ ). This is an algorithmic-based technique and usually done automatically.

Recently, model checking has been used to verify agent-based systems [1,2,3,4]. Verifying these systems is becoming more and more necessary because they are increasingly used in several critical application domains, such as e-commerce, simulation, distributed collaborative systems, etc [5,6,7]. In these systems, agents are

equipped with reasoning and communicative abilities. This is generally expressed using epistemic logics (logics about beliefs, knowledge, goals, etc.) and logic-based protocols [8]. Such protocols are modeled as a set of rules describing the allowed communicative acts in different situations. How an agent selects the communicative act to perform at a given moment is decided by his reasoning. In order to allow agents to flexibly and autonomously communicate within multi-agent systems, these protocols are specified as a set of policies, called dialogue games, about which agents can reason [9,10,11,12]. Dialogue games are interaction games in which each agent plays a move in turn by performing utterances according to a predefined set of logical rules. Dialogue game protocols are a combination of different dialogue games.

In this paper, we present an efficient *model checking algorithm* to verify interacting agent-based systems, in which agents have knowledge and beliefs and communicate by combining and reasoning about dialogue games. This algorithm is based on a tableau-based technique we developed in [13]. In this paper, we focus on the algorithmic description of this technique and on its termination and complexity. We specify a dialogue game protocol as a transition system in which transitions are labeled with communicative acts. Such acts are modeled as actions performed by agents *on Propositional Commitments (PC)*, for example, creating, accepting, or challenging a propositional commitment [10]. Propositional commitments are used to capture the *public utterances* in the sense that each utterance is viewed as a propositional commitment.

To use model checking, we specify dialogue game protocols and the properties to be verified in a new logic extending CTL\* by adding formulae representing propositional commitments. The verification method is based on the translation of formulae into a variant of alternating tree automata called *Alternating Büchi Tableau Automata (ABTA)* [14]. Unlike the model checking algorithms proposed in the literature, our on-the-fly efficient algorithm uses only one depth-first search instead of two. This is due to the fact that our algorithm explores directly the product graph of the dialogue game protocol and the ABTA representing the property to be verified using the sign of the nodes.

**Paper Overview.** The rest of the paper is organized as follows. In Section 1, we summarize and discuss related work. In Section 2, we develop a logic for communicating agents that we use to specify the properties to be checked. Section 3 presents the tableau rules associated to this logic. Section 4 presents the specification of dialogue game protocols agents use to communicate and gives some examples of the properties to be checked. In Section 5, we discuss the model checking technique of these protocols using tableau rules. In Section 6, we prove the termination property of the technique and we discuss its complexity. Section 7 concludes the paper.

## 1. Related Work

Bernholtz, Vardi, and Wolper [15] argued that *alternating tree automata* are the key to a comprehensive and satisfactory automata-theoretic framework for branching temporal logics. Alternating tree automata on infinite trees generalize the standard notion of non-deterministic tree automata by allowing several successor states to go down along the same branch of the tree. Tree automata generalize sequential automata in the following way: on a given binary tree, the automaton starts its computation at the root in an initial

state and then simultaneously works down the paths of the tree level by level. The transition relation specifies the two states that are the two sons of a node. The tree automaton accepts the tree if there is a run built up in this fashion which is *successful*. A run is successful if all its paths are successful in a sense given by an acceptance condition for sequential automata.

The model checking approach we use in this paper is based on an alternative view of model checking proposed by Bhat and Cleaveland [16] and Bhat et al. [14]. This view relies on translating formulae into intermediate structures, *Alternating Büchi Tableau Automata* (ABTA). Unlike the other model checking techniques, this technique allows us to verify not only temporal formulae, but also action formulae. Because our logic for communicating agents is based on an action theory, this technique is more suitable. This approach is called *tableau-based model checking* [13].

Recently, the verification of agent-based systems has become an attractive field of research and several proposals have been put forward. Some of these proposals use existing model checkers (for example SPIN and JPF2) by translating some agent specification languages (for example MABLE and AgentSpeak) to the languages used by these model checkers [1,2,17]. Other proposals adapt some model checking techniques (for example bounded and unbounded model checking) and propose new algorithms for verifying temporal and epistemic properties [4,5,6]. Giordano and her colleagues [3] addressed the problem of specifying and verifying systems of communicating agents in a Dynamic Linear Time Temporal Logic (DLTL).

Except the work done in [3], all the other proposals on model checking of agent-based systems are based only on temporal and epistemic logics. In this paper, we propose a model checking-based verification of dialogue game protocols using a temporal and dynamic logic. In contrast to [3], the dynamic aspect of our logic is represented by action formulae and not by strengthening the *until* operator by indexing it with the regular programs of dynamic logic. Our protocols are specified as actions that agents apply to propositional commitments. In addition, the model checking procedure that we propose allows us to verify not only that the dialogue game protocol (the theoretical model) satisfies a given property, but also that the tableau semantics of the communicative acts is respected. The idea is to integrate this semantics in the specification of the protocol, and then to propose a parsing method to verify that the protocol specification respects the semantic definition. Consequently, if agents respect these protocols, then they also respect the semantics of the communicative acts. We have here a mechanism for checking the agents' compliance with the semantics without accessing the agents' internal programs. Indeed, we have only one procedure to verify: 1) the correctness of the protocols relative to the properties that the protocols should satisfy; and 2) the conformance of agents to the semantics of the communicative acts. The purpose of this technique is to verify the temporal properties of the protocol and to ensure that the structures of the communicative acts are the same in both the protocol and the specification.

To our knowledge, until now there is no work that addressed the verification problem of agent-based systems communicating by dialogue game protocols. The contribution of this paper is an efficient algorithm for model checking software interacting agent-based systems and its termination and soundness proofs.

## 2. A Logic for Communicating Agents

### 2.1. Syntax

In this section, we present CTL\*<sup>CA</sup> an extended logic from CTL\* for Communicative Agents. This logic extends CTL\* by adding propositional commitments and action formulae. In what follows we use  $p, p_1, p_2, \dots$  to range over the set of atomic propositions  $\Phi_p$ . The syntax of this logic is as follows:

$$\begin{aligned}\mathcal{S} &:= p \mid \neg \mathcal{S} \mid \mathcal{S} \wedge \mathcal{S} \mid \mathcal{S} \vee \mathcal{S} \mid A\mathcal{P} \mid E\mathcal{P} \\ \mathcal{P} &:= \mathcal{S} \mid \mathcal{P} \wedge \mathcal{P} \mid \mathcal{P} \vee \mathcal{P} \mid X^+ \mathcal{P} \mid X^- \mathcal{P} \mid \mathcal{P} U^+ \mid \mathcal{P} U^- \mid \mathcal{P} \mid \mathcal{P} .: \mathcal{P} \\ &\quad \mid C(Ag_1, PC(Ag_1, Ag_2, t, \mathcal{P})) \\ &\quad \mid Act(Ag_i, PC(Ag_1, Ag_2, t, \mathcal{P}))\end{aligned}$$

The formulae generated by  $\mathcal{S}$  are called state formulae, while those generated by  $\mathcal{P}$  are called path formulae. We use  $\psi, \psi_1, \psi_2, \dots$  to range over state formulae and  $\phi, \phi_1, \phi_2, \dots$  to range over path formulae. The meaning of most of the constructs is straightforward (from CTL\* with next ( $X^+$ ), previous ( $X^-$ ), until ( $U^+$ ), and since ( $U^-$ ) operators). The formula  $\phi_1 .: \phi_2$  means that  $\phi_1$  is an argument for  $\phi_2$ . We can read this formula:  $\phi_1$ , so  $\phi_2$ . This operator introduces argumentation as a logical relation between path formulae.

The formula  $C(Ag_1, PC(Ag_1, Ag_2, t, \mathcal{P}))$  means that agent  $Ag_1$  commits at the moment  $t$  towards agent  $Ag_2$  that the path formula  $\mathcal{P}$  is true. The formula  $Act(Ag_i, PC(Ag_1, Ag_2, t, \mathcal{P}))$  means that agent  $Ag_i$  ( $i \in \{1, 2\}$ ) performs an action on the propositional commitment made by  $Ag_1$  towards  $Ag_2$ . The set of actions performed on propositional commitments are *Withdraw*, *Satisfy*, *Violate*, *Reactivate*, *Challenge*, *Accept*, *Refuse*, *Justify*, *Attack*, *Defend* (see [9] for more details).

### 2.2. Semantics

The formal model  $M$  associated to this logic corresponds to the dialogue game protocol agents use to communicate. Formally, this model is defined as follows:

$M = \langle S_m, Lab_m, Act_m, \xrightarrow{Act_m}, Agt, R_{PC}, S_{m_0} \rangle$  where:  $S_m$  is a set of states;  $Lab_m : S_m \rightarrow 2^{\Phi_p}$  is the labeling state function;  $Act_m$  is the set of actions performed on Propositional commitments;  $\xrightarrow{Act_m} \subseteq S_m \times Act_m \times S_m$  is the transition relation;  $Agt$  is a set of agents;  $R_{PC} : S_m \times Agt \times Agt \rightarrow 2^\sigma$  with  $\sigma$  is the set of all paths in  $M$  is an accessibility modal relation that associates to a state  $s_m$  the set of paths representing the propositional commitment along which an agent can commit towards another agent;  $s_{m_0}$  is the start state. The paths that path formulae are interpreted over have the form  $x^i = s_{m_i} \xrightarrow{\alpha_{i+1}} s_{m_{i+1}} \xrightarrow{\alpha_{i+2}} s_{m_{i+2}} \dots$  where  $x^i \in \sigma$ ,  $s_{m_i}, s_{m_{i+1}}, \dots$  are states and  $\alpha_{i+1}, \alpha_{i+2}, \dots$  are actions.

The semantics of  $\text{CTL}^{*\text{CA}}$  state formulae is as usual (semantics of  $\text{CTL}^*$ ). A path satisfies a state formula if the initial state in the path does. Along a path  $x^i$ ,  $\phi_1 \therefore \phi_2$  holds if  $\phi_1$  is true and at next time if  $\phi_1$  is true then  $\phi_2$  is true. Formally:

$$x^i \models_M \phi_1 \therefore \phi_2 \text{ iff } x^i \models_M \phi_1 \& x^{i+1} \models_M \phi_1 \Rightarrow \phi_2$$

A path  $x^i$  satisfies  $C(Ag_1, PC(Ag_1, Ag_2, t, \phi))$  if  $C$  is in the label of the first transition on this path and if every accessible path to  $Ag_1$  towards  $Ag_2$  from the first state of the path using  $R_{PC}$  satisfies  $\phi$ . Formally:

$$\begin{aligned} x^i \models_M C(Ag_1, PC(Ag_1, Ag_2, t, \phi)) \text{ iff} \\ \alpha_{i+1} = C \& \forall x^i \in \sigma, x^i \in R_{PC}(s_{m_i}, Ag_1, Ag_2) \Rightarrow x^i \models_M \phi \end{aligned}$$

A path  $x^i$  satisfies  $Act(Ag_i, PC(Ag_1, Ag_2, t, \phi))$  if  $Act$  is in the label of the first transition on this path and if in the past ( $P$ )  $Ag_1$  has already created the social commitment. Formally:

$$x^i \models_M Act(Ag_1, PC(Ag_1, Ag_2, t, \phi)) \text{ iff } \alpha_{i+1} = Act \& P(C(Ag_1, PC(Ag_1, Ag_2, t, \phi)))$$

We notice that the past ( $P$ ) and future ( $F$ ) operators are abbreviations from until operator ( $U$ ) in the usual way of  $\text{CTL}^*$  logic.

### 3. Tableau Rules for $\text{CTL}^{*\text{CA}}$

Tableau-based algorithms for model checking are based on the use of assertions and tableau rules which are *proof rules*. Assertions are typically of the form  $s \vdash_M \phi$  and mean that state  $s$  in model  $M$  satisfies the formula  $\phi$ . Using a set of tableau rules we aim to prove the truth or falsity of assertions. But unlike traditional proof systems which are bottom-up approaches, tableau-based algorithms work in a *top-down* or *goal-oriented* fashion. Tableau rules are used in order to prove a certain formula by inferring when a state in a Kripke structure satisfies such a formula. According to this approach, we start from a goal, and we apply a proof rule and determine the sub-goals to be proven. The proof rules are designed so that the goal is true if all the sub-goals are true. The advantage of this method is that the state space is explored in a need-driven fashion. The algorithm searches only the part of the state space that needs to be explored to prove or disprove a certain formula.

The tableau rules of  $\text{CTL}^{*\text{CA}}$  are given in Figures 1, 2, 3 and 4. We introduce a syntactical operator “?” to express the tableau rule of the challenge action. Semantically, “? $\psi$ ” means that, a given agent does not know whether  $\psi$  is true or not.

Tableau rules enable us to define top-down proof systems. The idea is: given a formula, we apply a tableau rule and determine the sub-formulae to be proven. Tableau rules are inference rules used in order to prove a formula by proving all the sub-formulae. The labels of these rules are the labels of states in the automata constructed from a given formula. For example, rule  $R1$  of Figure 1 labeled by “ $\wedge$ ” indicates that  $\psi_1$  and  $\psi_2$  are the two sub-formulae of  $\psi_1 \wedge \psi_2$ . This means that, in order to prove that a

state labeled by " $\wedge$ " satisfies the formula  $\psi_1 \wedge \psi_2$ , we have to prove that the two children of this state satisfy  $\psi_1$  and  $\psi_2$  respectively. According to rule  $R2$ , in order to prove that a state labeled by " $\vee$ " satisfies the formula  $\psi_1 \vee \psi_2$ , we have to prove that one of the two children of this state satisfies  $\psi_1$  or  $\psi_2$ . Rule  $R3$  labeled by " $\vee$ " indicates that  $\psi$  is the sub-formula to be proved in order to prove that a state satisfies  $E(\psi)$ . According to rule  $R4$  (resp.  $R5$ ), the formula  $\neg\psi$  (resp.  $? \psi$ ) is satisfied in a state labeled by " $\neg$ " (resp.  $?$ ), if this state has a successor representing  $\psi$ . Rule  $R6$  is defined in the usual way where  $\Phi$  is a set of path formulae.

$R1 \quad \wedge : \frac{\psi_1 \wedge \psi_2}{\psi_1 \psi_2}$	$R2 \quad \vee : \frac{\psi_1 \vee \psi_2}{\psi_1 \psi_2}$	$R3 \quad \vee : \frac{E(\psi)}{\psi}$
$R4 \quad \neg : \frac{\neg\psi}{\psi}$	$R5 \quad ?: \frac{? \psi}{\psi}$	$R6 \quad \neg : \frac{A(\Phi)}{E(\neg\Phi)}$

**Figure 1.** Tableau rules for propositional and universal formulas

The label " $<C>$ " (rule  $R7$ ) is the label associated with the creation action of a propositional commitment  $PC$ . According to this rule, in order to prove that a state satisfies  $C(Ag_1, PC(Ag_1, Ag_2, t, \phi))$ , we have to prove that an accessible state via a transition labeled by the creation action satisfies the sub-formula  $PC(Ag_1, Ag_2, t, \phi)$ . The rules  $R8$  to  $R17$  are defined in the same way.

Rule  $R18$  of Figure 3 indicates that  $E(\phi)$  is the sub-formula of the formula  $E(PC(Ag_1, Ag_2, t, \phi))$ . Thus, in order to prove that a state satisfies  $E(PC(Ag_1, Ag_2, t, \phi))$ , we have to prove that the accessible state via a transition labeled by " $[PC_{Ag_1}]$ " satisfies  $E(\phi)$ .

Finally, the rules  $R19$  to  $R27$  of Figure 4 are defined in the usual way. For example, according to rule  $R24$ , in order to prove that a state satisfies  $E(X^+ \phi)$ , we have to prove that the next state via the transition labeled by " $X^+$ " satisfies the sub-formula  $E(\phi)$ .

## 4. Protocol for Communicating Agents

### 4.1. Protocol Specification

In this section, we define the theoretical model of our model checking procedure. This model specifies the dialogue game protocols. These protocols are specified as a set of rules describing the entry condition, the dynamics and the exit condition of the protocol [10]. These rules can be specified in the logic for communicating agents as action formulae (actions on propositional commitments). We define these protocols as transition systems. The purpose of these transition systems is to describe not only the sequence of the allowed actions (classical transition systems), but also the structure of these actions. The states of these transition systems are sub-transition systems (called *structure transition systems*) describing the structure of the actions labeling the entry transitions. Defining transition systems in such a way allows for the verification of: 1)

the correctness of the protocol (if the model of the protocol satisfies the properties that the protocol should specify); 2) the compliance to the structure of the communicative actions (if the specification of the protocol respects the structure).

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$$\begin{aligned}
 R7 < C >: & \frac{E(\Phi, C(Ag_1, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, PC(Ag_1, Ag_2, t, \phi))} \\
 R8 < W >: & \frac{E(\Phi, Withdraw(Ag_1, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, \neg PC(Ag_1, Ag_2, t, \phi))} \\
 R9 < S_{PC}^{Ag1} >: & \frac{E(\Phi, Satisfy(Ag_1, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, \phi)} \\
 R10 < V_{PC}^{Ag1} >: & \frac{E(\Phi, Violate(Ag_1, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, \neg \phi)} \\
 R11 < Rea >: & \frac{E(\Phi, Reactivate(Ag_1, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, PC(Ag_1, Ag_2, t, \phi))} \\
 R12 < Ch >: & \frac{E(\Phi, Challenge(Ag_2, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, PC(Ag_2, Ag_1, t', ?\phi))} \\
 R13 < Acc >: & \frac{E(\Phi, Accept(Ag_2, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, PC(Ag_2, Ag_1, t', \phi))} \\
 R14 < Ref >: & \frac{E(\Phi, Refuse(Ag_2, PC(Ag_1, Ag_2, t, \phi)))}{E(\Phi, PC(Ag_2, Ag_1, t', \neg \phi))} \\
 R15 < Jus >: & \frac{E(\Phi, Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' :: \phi)))}{E(\Phi, PC(Ag_1, Ag_2, t, \phi' :: \phi))} \\
 R16 < Att >: & \frac{E(\Phi, Attack(Ag_2, PC(Ag_1, Ag_2, t, \phi' :: \neg \phi)))}{E(\Phi, PC(Ag_2, Ag_1, t', \phi' :: \neg \phi))} \\
 R17 < Def >: & \frac{E(\Phi, Defend(Ag_1, PC(Ag_1, Ag_2, t, \phi' :: \phi)))}{E(\Phi, PC(Ag_1, Ag_2, t', \phi' :: \phi))}
 \end{aligned}$$


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**Figure 2.** Tableau rules for action formulas

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$$R18 [PC_{Ag_1}]: \frac{E(\Phi, PC(Ag_1, Ag_2, t, \phi))}{E(\Phi, \phi)}$$


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**Figure 3.** Tableau rule for propositional commitment formula

$R19 \Leftrightarrow : \frac{E(\Phi, l)}{l, E(\Phi)}$	$R20 \wedge : \frac{E(\Phi, \phi_1 \wedge \phi_2)}{E(\Phi, \phi_1, \phi_2)}$	$R21 \vee : \frac{E(\Phi, \phi_1 \vee \phi_2)}{E(\Phi, \phi_1) E(\Phi, \phi_2)}$
$R22 ? : \frac{E(\Phi, ?\psi)}{E(\Phi, \psi)}$		
$R23 X^- : \frac{E(\Phi, X^- \phi_1, \dots, X^- \phi_n)}{E(\Phi, \phi_1, \dots, \phi_n)}$		$R24 X^+ : \frac{E(\Phi, X^+ \phi_1, \dots, X^+ \phi_n)}{E(\Phi, \phi_1, \dots, \phi_n)}$
$R25 \wedge : \frac{E(\Phi, \phi_1 \therefore \phi_2)}{E(\Phi, \phi_1, X^+(\neg\phi_1 \vee \phi_2))}$		
$R26 \vee : \frac{E(\Phi, \phi_1 U^- \phi_2)}{E(\Phi, \phi_2) E(\Phi, \phi_1, X^-(\phi_1 U^- \phi_2))}$	$R27 \vee : \frac{E(\Phi, \phi_1 U^+ \phi_2)}{E(\Phi, \phi_2) E(\Phi, \phi_1, X^+(\phi_1 U^+ \phi_2))}$	

**Figure 4.** Tableau rules for state formulas

The definition of the transition system of dialogue game protocols is given by the following definitions:

**Definition 1** A structure transition system  $T'$  describing the structure of an action formula is a 6-tuple  $\langle S', \text{Lab}', F, Ls', R, \rightarrow, s'_0 \rangle$  where:

- $S'$  is a set of states,
- $\text{Lab}' : S' \rightarrow 2^{\Phi_p}$  is the labeling state function, where  $\Phi_p$  is the set of atomic propositions,
- $F$  is a sub-set of CTL\*<sup>CA</sup> formulae ( $F$  does not include the action formulae i.e. Satisfy, Accept, etc.),
- $Ls' : S' \rightarrow F$  is a function associating to each state a formula,
- $R \in \{ \wedge, \vee, \neg, ?, \Leftrightarrow, X^+, X^-, PC_{Ag} \}$  is the set of tableau rule labels (without the rules for action formulae),
- $\rightarrow \subseteq S' \times R \times S'$  is the transition relation,
- $s'_0$  is the start state.

Intuitively, states  $s'$  contain the sub-formulae of the action formulae, and the transitions are labeled by operators associated with the formula of the starting state. Semantic transition systems enable us to describe the semantics of formulae by sub-formulae connected by logical operators. Thus, there is a transition between states  $s'_i$  and  $s'_j$  iff  $L'(s'_j)$  is a sub-formula or an semantically equivalent formula of  $L'(s'_i)$ . Following traditional usage we write  $s \rightarrow^r s'$  instead of  $\langle s, r, s' \rangle \in \rightarrow$  where  $s, s' \in S'$  and  $r \in R$ .

**Definition 2** A transition system  $T$  for a dialogue game protocol is a 6-tuple  $\langle S, \text{Lab}, \emptyset, L, \text{Act}, \rightarrow, s_0 \rangle$  where:

- $S$  is a set of states,
- $\text{Lab} : S \rightarrow 2^{\Phi_p}$  is the labeling state function,
- $\emptyset$  is a set of structure transition systems with  $\epsilon \in \emptyset$  is the empty structure transition system,

- $L : S \rightarrow \wp$  is the function associating to a state  $s \in S$  a structure transition system  $T' \in \wp$  describing the semantics of the action labeling the entry transition,
- $Act \in \{C, Withdraw, Satisfy, Accept, Refuse, Challenge, Justify, Defend, Attack\}$  is the set of actions,
- $\rightarrow \subseteq S \times Act \times S$  is the transition relation,
- $s_0$  is the start state with  $L(s_0) = \epsilon$  (i.e. there is no structure transition system in  $s_0$ ).

The transitions are labeled by the actions applied to propositional commitments. We write  $s \rightarrow s'$  instead of  $\langle s, \bullet, s' \rangle \in \rightarrow$  where  $s, s' \in S$  and  $\bullet \in Act$ . Figure 5 illustrates a part of a transition system for a dialogue game protocol.

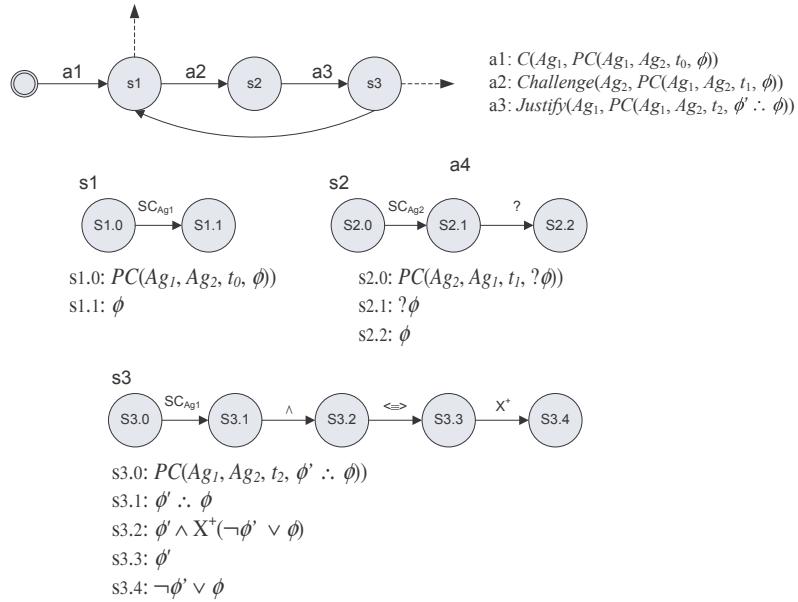


Figure 5. A part of a transition system for a dialogue game protocol

#### 4.2. Examples of Protocol Properties

The properties to be verified in the dialogue game protocols specified in CTL\*<sup>CA</sup> are action and temporal properties. For example, we can verify if a model of dialogue game protocol satisfies the following property:

$$AG^+(Challenge(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \Rightarrow F^+Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' .. \phi)))$$

This property says that in all paths ( $A$ ), globally ( $G^+$ ), if an agent  $Ag_2$  challenges the content  $\phi$  of an  $Ag_1$ 's propositional commitment ( $PC$ ), then in the future ( $F^+$ )  $Ag_1$  will justify this content by an argument  $\phi' .. \phi$ .

Another interesting property to be checked in dialogue games is related to the communicative acts an agent is allowed to perform at a given moment. For example, it

is prohibited to attack a commitment content if the addressee did not commit about this content. This property is specified using the past operator  $F^+$  as follows:

$$AG^+(Attack(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \Rightarrow F^+C(Ag_1, PC(Ag_1, Ag_2, t, \phi)))$$

A third property capturing the deontic notion of propositional commitments is given by the following formula:

$$\begin{aligned} AG^+(Attack(Ag_2, PC(Ag_1, Ag_2, t, \phi') \therefore \neg \phi)) \Rightarrow \\ (F^+Defend(Ag_1, PC(Ag_1, Ag_2, t, \phi'') \therefore \phi) \\ \vee F^+Attack(Ag_1, PC(Ag_2, Ag_1, t', \phi'') \therefore \neg \phi')) \\ \vee F^+Accept(Ag_1, PC(Ag_2, Ag_1, t', \phi'))) \end{aligned}$$

Using this property, we can verify if a model of a dialogue game protocol satisfies the fact that if an agent  $Ag_2$  attacks the content of an agent  $Ag_1$ 's propositional commitment  $PC$ , then  $Ag_1$  will defend its propositional commitment content, attack the  $Ag_2$ 's argument or accept it.

## 5. Model Checking Technique

In this section, we use a combination of an automata-theoretic approach and a tableau-based approach to model-checking communicating agent-based systems.

### 5.1. Alternating Büchi Tableau Automata for $CTL^{*CA}$

As a kind of Büchi automata, ABTAs [14] are used in order to prove properties of *infinite* behavior. These automata can be used as an intermediate representation for system properties. Let  $\Phi_p$  be the set of atomic propositions and let  $\mathfrak{R}$  be a set of tableau rule labels defined as follows:

$\mathfrak{R} = \{\wedge, \vee, \neg, ?\} \cup \mathfrak{R}_{Act} \cup \mathfrak{R}_{\neg Act} \cup \mathfrak{R}_{SC} \cup \mathfrak{R}_{Set}$  where  $\mathfrak{R}_{Act}$ ,  $\mathfrak{R}_{SC}$  and  $\mathfrak{R}_{Set}$  are defined as follows:

$$\mathfrak{R}_{Act} = \{\langle C \rangle, \langle W \rangle, \langle S_{PC}^{Ag} \rangle, \langle V_{PC}^{Ag} \rangle, \langle Rea \rangle, \langle Ch \rangle, \langle Acc \rangle, \langle Ref \rangle, \langle Jus \rangle, \langle Att \rangle, \langle Def \rangle\}.$$

$$\mathfrak{R}_{SC} = \{[PC_{Ag}] \}.$$

$$\mathfrak{R}_{Set} = \{\langle \equiv \rangle, X^+, X^- \}.$$

The associated tableau rules are given in Figures 1, 2, 3 and 4.

Formally, we define ABTAs for  $CTL^{*CA}$  logic as follows:

**Definition 3** An ABTA for  $CTL^{*CA}$  is a 5-tuple  $\langle Q, l, \rightarrow, q_0, F \rangle$ , where:

- $Q$  is a finite set of states,
- $l: Q \rightarrow \Phi_p \cup \mathfrak{R}$  is the state labeling,
- $\rightarrow \subseteq Q \times Q$  is the transition relation,
- $q_0$  is the start state,
- $F \subseteq 2^Q$  is the acceptance condition.

ABTAs allow us to encode “*top-down proofs*” for temporal formulae. Indeed, an ABTA encodes a proof schema in order to prove, in a goal-directed manner, that a transition system satisfies a temporal formula.

### **Example**

*Let us consider the following example. We would like to prove that a state s in a transition system satisfies a temporal formula of the form  $F1 \wedge F2$ , where  $F1$  and  $F2$  are two formulae. Regardless of the structure of the system, there would be two sub-goals if we want to prove this in a top-down, goal-directed manner. The first would be to prove that s satisfies  $F1$ , and the second would be to prove that s satisfies  $F2$ . Intuitively, an ABTA for  $F1 \wedge F2$  would encode this “proof structure” using states for the formulae  $F1 \wedge F2$ ,  $F1$ , and  $F2$ . A transition from  $F1 \wedge F2$  to each of  $F1$  and  $F2$  should be added to the ABTA and the labeling of the state for  $F1 \wedge F2$  being “ $\wedge$ ” which is the label of a certain rule. Indeed, in an ABTA, we can consider that: 1) states correspond to “formulae”, 2) the labeling of a state is the “logical operator” used to construct the formula, and 3) the transition relation represents a “sub-goal” relationship.*

In order to decide about the satisfaction of formulae, we use the notion of the *accepting runs* of an ABTA on a transition system. These runs are not considered to be finite, but rather infinite, while cycling infinitely many times through acceptance states. In order to define this notion of the ABTA’s run, we need to introduce three types of nodes: *positive*, *negative* and *neutral* (neither positive nor negative). Intuitively, nodes classified positive are nodes that correspond to a formula without negation (for example  $C(Ag_1, PC(Ag_1, Ag_2, t, \phi))$ ), and negative nodes are nodes that correspond to a formula with negation (for example  $\neg Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))$ ). Neutral nodes are used in order to verify the semantics of an action formula ( $act \in Act$ ) written in the formula to be verified under the form  $\neg act$ . From the semantic point of view,  $\neg act$  means that the action  $act$  is not performed. For example, if in the formula to be verified appears the sub-formula:  $\neg Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))$ , we use in the ABTA neutral nodes in order to verify the semantics of:  $Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))$ . The reason is that in transition systems, and consequently in the sub-transition systems, we have only action formulae without negation, whereas in the formula to be verified, we can have action formulae with negation. We note that we can not use here negative nodes because we do not interested in the formula in itself (i.e. in the example  $\neg Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))$ ) but in the semantics of the underlying action (i.e.  $Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))$ ). In other words, we are not interested in the semantics of the negation action, but in the semantics of the action itself. We note here that in order to verify that an action formula  $\neg act$  is satisfied, we have to verify that from a given state there is no transition in the transition system labeled by  $act$ . Definition 4 gives the definition of this notion of run. In this definition, elements of the set  $S$  of states are denoted  $s_i$  or  $t_i$ . The explanation of the different clauses is given after the definition.

**Definition 4** A run of an ABTA  $B = \langle Q, l, \rightarrow, q_0, F \rangle$  on a transition system  $T = \langle S, Lab, \wp, L, Act, \rightarrow, s_0 \rangle$  is a graph in which the nodes are classified as positive, negative or neutral and are labeled by elements of  $Q \times S$  as follows:

1. The root of the graph is a positive node and is labeled by  $\langle q_0, s_0 \rangle$ .
2. If  $\varphi$  is a positive node with label  $\langle q, s_i \rangle$  such that  $l(q) = \neg$  and  $q \rightarrow q'$ , then  $\varphi$  has one negative successor labeled  $\langle q', s_i \rangle$  and vice versa.
- Otherwise, for a positive node  $\varphi$  labeled by  $\langle q, s_i \rangle$ :
  3. If  $l(q) \in \Phi_p$  then  $\varphi$  is a leaf.
  4. If  $l(q) \in \{\wedge, \Leftrightarrow\}$  and  $\{q' \mid q \rightarrow q'\} = \{q_1, \dots, q_m\}$ , then  $\varphi$  has positive successors  $\varphi_1, \dots, \varphi_m$  with  $\varphi_j$  labeled by  $\langle q_j, s_i \rangle$  ( $1 \leq j \leq m$ ).
  5. If  $l(q) = \vee$  then  $\varphi$  has one positive successor  $\varphi'$  labeled by  $\langle q', s_i \rangle$  for some  $q' \in \{q' \mid q \rightarrow q'\}$ .
  6. If  $l(q) = X^+$  and  $q \rightarrow q'$  and  $\{s' \mid s_i \xrightarrow{*} s'\} = \{t_1, \dots, t_m\}$  where  $\bullet \in Act$ , then  $\varphi$  has positive successors  $\varphi_1, \dots, \varphi_m$  with  $\varphi_j$  labeled by  $\langle q', t_j \rangle$  ( $1 \leq j \leq m$ ).
  7. If  $l(q) = X^-$  and  $q \rightarrow q'$  and  $\{s' \mid s' \xrightarrow{*} s_i\} = \{t_1, \dots, t_m\}$  where  $\bullet \in Act$ , then  $\varphi$  has positive successors  $\varphi_1, \dots, \varphi_m$  with  $\varphi_j$  labeled by  $\langle q', t_j \rangle$  ( $1 \leq j \leq m$ ).
  8. If  $l(q) = \langle \bullet \rangle$  where  $\bullet \in Act$  and  $q \rightarrow q'$ , and  $s_i \xrightarrow{*} s_{i+1}$  then  $\varphi$  has one positive successor  $\varphi'$  labeled by  $\langle q', s_{i+1,0} \rangle$  where  $s_{i+1,0}$  is the initial state of the semantic transition system of  $s_{i+1}$ .
  9. If  $l(q) = \langle \neg \bullet \rangle$  where  $\bullet \in \neg Act$  and  $q \rightarrow q'$ , and  $s_i \xrightarrow{*} s_{i+1}$  then  $\varphi$  has one neutral successor  $\varphi'$  labeled by  $\langle q', s_{i+1,0} \rangle$  where  $s_{i+1,0}$  is the initial state of the semantic transition system of  $s_{i+1}$ .
  10. If  $l(q) = \langle \bullet \rangle$  where  $\bullet \in \neg Act$  and  $q \rightarrow q'$ , and  $s_i \xrightarrow{*} s_{i+1}$  where  $\bullet \neq \neg \bullet'$  and  $\bullet' \in Act$ , then  $\varphi$  has one positive successor  $\varphi'$  labeled by  $\langle q', s_{i+1} \rangle$ .
  - Otherwise, for a negative node  $\varphi$  labeled by  $\langle q, s_i \rangle$ :
    11. If  $l(q) \in \Phi_p$  then  $\varphi$  is a leaf.
    12. If  $l(q) \in \{\vee, \Leftrightarrow\}$  and  $\{q' \mid q \rightarrow q'\} = \{q_1, \dots, q_m\}$ , then  $\varphi$  has negative successors  $\varphi_1, \dots, \varphi_m$  with  $\varphi_j$  labeled by  $\langle q_j, s_i \rangle$  ( $1 \leq j \leq m$ ).
    13. If  $l(q) = \wedge$  then  $\varphi$  has one negative successor  $\varphi'$  labeled by  $\langle q', s_i \rangle$  for some  $q' \in \{q' \mid q \rightarrow q'\}$ .
    14. If  $l(q) = X^+$  and  $q \rightarrow q'$  and  $\{s' \mid s_i \xrightarrow{*} s'\} = \{t_1, \dots, t_m\}$  where  $\bullet \in Act$ , then  $\varphi$  has negative successors  $\varphi_1, \dots, \varphi_m$  with  $\varphi_j$  labeled by  $\langle q', t_j \rangle$  ( $1 \leq j \leq m$ ).
    15. If  $l(q) = X^-$  and  $q \rightarrow q'$  and  $\{s' \mid s' \xrightarrow{*} s_i\} = \{t_1, \dots, t_m\}$  where  $\bullet \in Act$ , then  $\varphi$  has negative successors  $\varphi_1, \dots, \varphi_m$  with  $\varphi_j$  labeled by  $\langle q', t_j \rangle$  ( $1 \leq j \leq m$ ).
    16. If  $l(q) = \langle \bullet \rangle$  where  $\bullet \in Act$  and  $q \rightarrow q'$ , and  $s_i \xrightarrow{*} s_{i+1}$  then  $\varphi$  has one negative successor  $\varphi'$  labeled by  $\langle q', s_{i+1,0} \rangle$  where  $s_{i+1,0}$  is the initial state of the semantic transition system of  $s_{i+1}$ .
    17. If  $l(q) = \langle \neg \bullet \rangle$  where  $\bullet \in \neg Act$  and  $q \rightarrow q'$ , and  $s_i \xrightarrow{*} s_{i+1}$  then  $\varphi$  has one neutral successor  $\varphi'$  labeled by  $\langle q', s_{i+1,0} \rangle$  where  $s_{i+1,0}$  is the initial state of the semantic transition system of  $s_{i+1}$ .
    18. If  $l(q) = \langle \bullet \rangle$  where  $\bullet \in \neg Act$  and  $q \rightarrow q'$ , and  $s_i \xrightarrow{*} s_{i+1}$  where  $\bullet \neq \neg \bullet'$  and  $\bullet' \in Act$ , then  $\varphi$  has one negative successor  $\varphi'$  labeled by  $\langle q', s_{i+1} \rangle$ .
    - Otherwise, for a neutral node  $\varphi$  labeled by  $\langle q, s_{i,j} \rangle$ :

19. If  $l(q) = \Leftrightarrow$  and  $\{q' \mid q \rightarrow q'\} = \{q_1, q_2\}$  such that  $q_1$  is a leaf, and  $s_{i,j}$  has a successor  $s_{i,j+1}$ , then  $\varphi$  has one positive leaf successor  $\varphi'$  labeled by  $\langle q_1, s_{i,j} \rangle$  and one neutral successor  $\varphi''$  labeled by  $\langle q_2, s_{i,j+1} \rangle$ .
20. If  $l(q) = \Leftrightarrow$  and  $\{q' \mid q \rightarrow q'\} = \{q_1, q_2\}$  such that  $q_1$  is a leaf, and  $s_{i,j}$  has no successor, then  $\varphi$  has one positive leaf successor labeled by  $\langle q_1, s_{i,j} \rangle$ .
- Otherwise, for a positive (negative) node  $\varphi$  labeled by  $\langle q, s_{i,j} \rangle$ :
  21. If  $l(q) = \Leftrightarrow$  and  $\{q' \mid q \rightarrow q'\} = \{q_1, q_2\}$  such that  $q_1$  is a leaf, and  $s_{i,j}$  has a successor  $s_{i,j+1}$ , then  $\varphi$  has one positive leaf successor  $\varphi'$  labeled by  $\langle q_1, s_{i,j} \rangle$  and one positive (negative) successor  $\varphi''$  labeled by  $\langle q_2, s_{i,j+1} \rangle$ .
  22. If  $l(q) = \Leftrightarrow$  and  $\{q' \mid q \rightarrow q'\} = \{q_1, q_2\}$  such that  $q_1$  is a leaf, and  $s_{i,j}$  has no successor, then  $\varphi$  has one positive leaf successor  $\varphi'$  labeled by  $\langle q_1, s_{i,j} \rangle$  and one positive (negative) successor  $\varphi''$  labeled by  $\langle q_2, s_{i,j} \rangle$ .
- Otherwise, for a positive (negative, neutral) node  $\varphi$  labeled by  $\langle q, s_{i,j} \rangle$ :
  23. If  $l(q) \in \{\wedge, \vee, ?, X^+, X^-, [PC_{Ag}]\}$  and  $\{q' \mid q \rightarrow q'\} = \{q_1\}$ , and  $s_{i,j} \xrightarrow{r} s_{i,j+1}$  such that  $r = l(q)$ , then  $\varphi$  has one positive (negative, neutral) successor  $\varphi'$  labeled by  $\langle q_1, s_{i,j+1} \rangle$ .

The notion of run of an ABTA on a transition system is a non-synchronized product graph of the ABTA and the transition system. This run uses the label of nodes in the ABTA ( $l(q)$ ), the transitions in the ABTA ( $q \rightarrow q'$ ), and the transitions in the transition system ( $s_i \rightarrow s_j$ ). The product is not synchronized in the sense that it is possible to use transitions in the ABTA while staying in the same state in the transition system (this is the case for example of the clauses 2, 4, and 5).

The second clause in the definition says that if we have a positive node  $\varphi$  in the product graph such that the corresponding state in the ABTA is labelled with  $\neg$  and we have a transition  $q \rightarrow q'$  in this ABTA, then  $\varphi$  has one negative successor labelled with  $\langle q', s \rangle$ . In this case we use a transition from the ABTA and we stay in the same state of the transition system. In the case of a positive node and if the current state of the ABTA is labelled with  $\wedge$ , all the transitions of this current state of the ABTA are used (clause 4). However, if the current state of the ABTA is labelled with  $\vee$ , only one arbitrary transition from the ABTA is used (clause 5). The intuitive idea is that in the case of  $\wedge$ , all the sub-formulae must be true in order to decide about the formula of the current node of the ABTA, and in the case of  $\vee$  only one sub-formula must be true.

The cases in which a transition of the transition system is used are:

1. The current node of the ABTA is labelled with  $X^+$  (which means a next state in the transition system) or  $X^-$  (which means a previous state in the transition system). This is the case of the clauses 6, 7, 14, and 15. In this case we use all the transitions from the current state  $s_i$  to next or previous states of the transition system.
2. The current state of the ABTA and a transition from the current state of the transition system are labelled with the same action. This is the case of the clauses 8 and 16. In this case, the current transition of the ABTA and the transition from the current state  $s_i$  of the transition system to a state  $s_{i+1,0}$  of the associated semantic transition system are used. The idea is to start the parsing of the formula coded in the semantic transition system.
3. The current state of the ABTA and a transition from the current state of the transition system are labelled with the same action which is preceded by  $\neg$  in the ABTA. This is the case of the clauses 9 and 17. In this case, the current transition of the ABTA and the

transition from the current state  $s_i$  of the transition system to a state  $s_{i+1}, o$  of the associated semantic transition system are used. The successor node is classified neutral. This allows us to verify the structure of the formula coded in the transition system.

**4.** The current state of the ABTA and a transition from the current state of the transition system are labelled with different actions where the state of the ABTA is labelled with a negative formula. This is the case of the clauses 10 and 18. In this case, the formula is satisfied, but its structure cannot be verified. Consequently, the current transition of the ABTA and the transition from the current state  $s_i$  of the transition system to a next state  $s_{i+1}$  are used. This means that, we do not visit the associated semantic transition system.

Finally, the clauses 19, 20, 21, 22, and 23 deal with the case of verifying the structure of the commitment formulae in the sub-transition systems. In these clauses, transitions  $s_{i,j} \rightarrow s_{i,j+1}$  are used. We note here that when  $s_{i,j}$  has no successor, the formula contained in this state is an atomic formula or a boolean formula whose all the sub-formulae are atomic (for example  $p \wedge q$  where  $p$  and  $q$  are atomic).

We also need to define the notion of *success* of a run for the correctness of the model checking. To define this notion, we first introduce *positive* and *negative paths*. In an ABTA, every infinite path has a suffix that contains either positive or negative nodes, but not both. Such a path is referred to as *positive* in the former case and *negative* in the latter.

Let  $p \in \Phi p$  and let  $s_i$  be a state in a transition system  $T$ . Then  $s_i \models_T p$  iff  $p \in Lab(s_i)$  and  $s_i \models_T \neg p$  iff  $p \notin Lab(s_i)$ .

Let  $s_{i,j}$  be a state in a semantic transition system of a transition system  $T$ . Then  $s_{i,j} \models_T p$  iff  $p \in Lab'(s_{i,j})$  and  $s_{i,j} \models_T \neg p$  iff  $p \notin Lab'(s_{i,j})$ .

**Definition 5** Let  $r$  be a run of ABTA  $B = \langle Q, l, \rightarrow, q_0, F \rangle$  on a transition system  $T = \langle S, Lab, \emptyset, L, Act, \rightarrow, s_0 \rangle$ . The run  $r$  is successful iff every leaf and every infinite path in  $r$  is successful. A successful leaf is defined as follows:

- 1- A positive leaf labeled by  $\langle q, s_i \rangle$  is successful iff  $s_i \models_T l(q)$  or  $l(q) = \langle \bullet \rangle$  where  $\bullet \in Act$  and there is no  $s_j$  such that  $s_i \xrightarrow{*} s_j$ .
- 2- A positive leaf labeled by  $\langle q, s_{i,j} \rangle$  is successful iff  $s_{i,j} \models_T l(q)$
- 3- A negative leaf labeled by  $\langle q, s_i \rangle$  is successful iff  $s_i \models_T \neg l(q)$  or  $l(q) = \langle \bullet \rangle$  where  $\bullet \in Act$  and there is no  $s_j$  such that  $s_i \xrightarrow{*} s_j$ .
- 4- A negative leaf labeled by  $\langle q, s_{i,j} \rangle$  is successful iff  $s_{i,j} \models_T \neg l(q)$
- 5- All neutral leaves are not successful.

A successful infinite path is defined as follows:

- 1- A positive path is successful iff  $\forall f \in F, \exists q \in f$  such that  $q$  occurs infinitely often in the path. This condition is called the Büchi condition.
- 2- A negative path is successful iff  $\exists f \in F, \forall q \in f, q$  does not occur infinitely often in the path. This condition is called the co-Büchi condition.

We note here that a positive or negative leaf labeled by  $\langle q, s \rangle$  such that  $l(q) = \langle \bullet \rangle$  where  $\bullet \in Act$  and there is no  $s'$  such that  $s \xrightarrow{*} s'$  is considered a successful leaf because we can not consider it unsuccessful. The reason is that it is possible to find a transition labeled by  $\bullet$  and starting from another state  $s''$  in the transition system. This is the case of the leaf labeled by  $(\langle Ch \rangle, s_0)$  in the Case Study we will discuss in Section 5.3 (see Figure 11). If we consider such a leaf unsuccessful, then even if we find a successful infinite path, the run will be considered unsuccessful. However this is false.

We also note that an ABTA  $B$  accepts a transition system  $T$  iff there exists a successful run of  $B$  on  $T$ .

### 5.2. Translation Procedure

The procedure for translating a CTL\*<sup>CA</sup> formula  $p = E\phi$  to an ABTA  $B$  uses goal-directed rules in order to build a tableau from this formula. Indeed, these proof rules are conducted in a top-down fashion in order to determine whether states satisfy properties or not. The tableau is constructed by exhaustively applying the rules contained in Figures 1, 2, 3 and 4 to  $p$ . Then,  $B$  can be extracted from this tableau as follows. First, we generate the states and the transitions. Intuitively, states will correspond to state formulae, with the start state being  $p$ . To generate new states from an existing state for a formula  $p'$ , we determine which rule is applicable to  $p'$ , starting with  $R1$ , by comparing the form of  $p'$  to the formula appearing in the “goal position” of each rule. Let  $rule(q)$  denote the rule applied at node  $q$ . The labeling function  $l$  of states is defined as follows. If  $q$  does not have any successor, then  $l(q) \in \Phi_p$ . Otherwise, the successors of  $q$  are given by  $rule(q)$ . The label of the rule becomes the label of the state  $q$ , and the sub-goals of the rule are then added as states related to  $q$  by transitions.

A tableau for a CTL\*<sup>CA</sup> formula  $p$  is a maximal proof tree having  $p$  as its root and constructed using rules  $R1-R27$ . If  $p'$  results from the application of a rule to  $p$ , then we say that  $p'$  is a child of  $p$  in the tableau. The height of a tableau is defined as the length of the longest sequence  $\langle p_0, p_1, \dots \rangle$ , where  $p_{i+1}$  is the child of  $p_i$  [18]. Finally, in order to compute the successful run of the generating ABTA, we should compute the acceptance states  $F$ . For this purpose we use the following definition.

**Definition 6** Let  $q$  be a state in an ABTA  $B$  and  $Q$  the set of all states. Suppose  $\phi = \phi_1 U^+ \phi_2 \in q^1$ . We define the set  $F_\phi$  as follows:

$$F_\phi = \{q' \in Q \mid (\phi \notin q' \text{ and } X^*\phi \notin q') \text{ or } \phi_2 \in q'\}.$$

The acceptance set  $F$  is defined as follows:

$$F = \{F_\phi \mid \phi = \phi_1 U^+ \phi_2 \text{ and } \exists q \in B, \phi \in q\}.$$

According to this definition, a state that contains the formula  $\phi$  or the formula  $X^*\phi$  is not an acceptance state. The reason is that according to Definition 4, there is a transition from a state containing  $\phi$  to a state containing  $X^*\phi$  and vice versa. Therefore, according to Definition 5, there is a successful run in the ABTA  $B$ . However, we can not decide about the satisfaction of a formula using this run. The reason is that in an infinite cycle including a state containing  $\phi$  and a state containing  $X^*\phi$ , we can not be sure that a state containing  $\phi_2$  is reachable. However, according to the semantics of  $U^+$ , the satisfaction of  $\phi$  needs that a state containing  $\phi_2$  is reachable while passing by states containing  $\phi_1$ .

### Case Study

Let us show a practical case on how a CTL\*<sup>CA</sup> formula is translated to an ABTA. We consider the following propositional formula:  $E(G^+F^+p)$ . In the context of dialogue

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<sup>1</sup> Here we consider “until” formula because is the formula that allows paths to be infinite.

game-based agents, this formula says that along some transitions, globally in the future a commitment content holds. The first step is to build the tableau for this formula using tableau rules. The first rule we can apply is  $R27$  labeled by " $\vee$ " for the until formula ( $G^+$  is an abbreviation defined from  $U^+$ ). The second rule is also  $R27$  for  $F^+p$  ( $F^+$  is also an abbreviation defined from  $U^+$ ). Thereafter rules  $R19$  and  $R24$  can be applied. We obtain the tableau illustrated in Figure 6 where the rule labels are indicated.

The ABTA obtained from this tableau is illustrated in Figure 7. In this ABTA, states (1), (3), (5) and (6) are the acceptance states according to Definition 6. The formula  $\phi$  we consider is the following:  $\phi = \text{True } U^+ p \equiv F^+p$ . Notice that  $\phi$  and  $X^+\phi$  do not appear in these states. State (5) is the acceptance state in the finite case. On the other hand,  $\phi$  appears in states (2) and (7), and  $X^+\phi$  appears in state (4). Therefore, these states are not in  $F_\phi$ . The path  $\Pi = (1, (2, 4, 7)^*)$  is not a valid proof of  $E(G^+F^+p)$ . However, a path that visits infinitely often the states (1), (3) and (6) is a valid (infinite) proof. The reason is that in such a path there is always a chance to meet the proposition  $p$  (state (3)). Therefore, this path satisfies the Büchi condition. The Büchi condition is not satisfied in the path  $\Pi$  since there is no chance to visit infinitely often a state containing  $p$ .

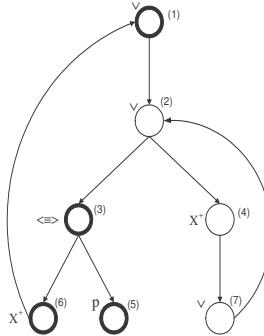
$\vee : E(G^+F^+p)$ (1)		
	$\vee : E(F^+p, X^+G^+F^+p)$ (2)	
		$X^+ : E(X^+F^+p, X^+G^+F^+p)$ (4)
$p$ (5)	$X^+ : E(X^+G^+F^+p)$ (6)	$\vee : E(F^+p, G^+F^+p)$ (7)
	$E(G^+F^+p)$	$E(F^+p, X^+G^+F^+p)$

Figure 6. The tableau for  $E(G^+F^+p)$

### 5.3. Model Checking Algorithm

The idea behind our model checking algorithm is to explore the product graph of an ABTA for  $\text{CLT}^{*\text{CA}}$  and a transition system for a dialogue game. This algorithm is *on-the-fly* (or *local*) algorithm consisting of checking if a transition system is accepted by an ABTA. This model checking is reduced to the emptiness of the Büchi automata [19].

Let  $T = \langle S, \text{Lab}, \wp, L, \text{Act}, \rightarrow, s_0 \rangle$  be a transition system for a dialogue game and let  $B = \langle Q, l, \rightarrow, q_0, F \rangle$  be an ABTA for  $\text{CLT}^{*\text{CA}}$ . The procedure consists of building the ABTA product  $B_\otimes$  of  $T$  and  $B$  while checking if there is a successful run in  $B_\otimes$ . The existence of such a run means that the language of  $B_\otimes$  is non-empty. The automaton  $B_\otimes$  is defined as follows:  $B_\otimes = \langle Q \times S, \rightarrow_{B_\otimes}, q_{0B_\otimes}, F_{B_\otimes} \rangle$ . There is a transition between two nodes  $\langle q, s \rangle$  and  $\langle q', s' \rangle$  iff there is a transition between these two nodes in some run of  $B$  on  $T$ . Intuitively,  $B_\otimes$  simulates all the runs of the ABTA. The set of accepting states  $F_{B_\otimes}$  is defined as follows:  $q_{0B_\otimes} \in F_{B_\otimes}$  iff  $q \in F$ .

Figure 7. The ABTA of the formula  $E(G^+ F^+ p)$ 

Unlike the algorithms proposed in [14, 16, 20], our algorithm uses only one depth-first search (DFS) instead of two. This is due to the fact that our algorithm explores directly the product graph using the sign of the nodes (positive, negative or neutral). In addition, unlike the algorithm proposed in [14], our algorithm does not distinguish between recursive and non-recursive nodes. Therefore, we do not take into account the strongly-connected components in the ABTA, but we use a marking algorithm that works on the product graph.

The pseudo-code of this algorithm is given in Figure 8. The idea is to construct the product graph while exploring it. However, in order to make it easy to understand, we omit the instructions relative to the addition of nodes in the product graph. The construction procedure is directly obtained from Definition 4. The algorithm uses the label of nodes in the ABTA, and the transitions in the product graph obtained from the transition system and the ABTA as explained in Definition 4.

In order to decide if the ABTA contains an infinite successful run, all the explored nodes are marked "visited". Thus, when the algorithm explores a visited node, it returns false if the infinite path is not successful. If the node is not already visited, the algorithm tests if it is a leaf. In this case, it returns false if the node is a non-successful leaf. If the explored node is not a leaf, the algorithm calls recursively the function DFS in order to explore the successors of this node. If this node is labeled by " $\wedge$ ", and signed neutrally or positively, then DFS returns false if one of the successors is false. However, if the node is signed negatively, DFS returns false if all the successors are false. A dual treatment is applied when the node is labeled by " $\vee$ ". We note that if the DFS does not explore a false node (i.e. it does not return false), then it returns true.

**Theorem 1 (Correctness)** *Let  $B$  an ABTA and  $T$  a transition system.  $DFS(q_0, s_0)$  returns true if and only if  $T$  is accepted by  $B$ .*

The proof of this theorem is developed in [9]<sup>2</sup>.

<sup>2</sup> The proof is developed in Chapter 8 and could be checked online:  
<http://users.encs.concordia.ca/~bentahar/Thesis/BNJ-Thesis1.pdf>

---

```

DFS(v = (q, s)): boolean {
    if v marked visited {
        if (sign(v) = "+" and not accepting(v)) or (sign(v) = "-" and accepting(v))
            return false
    } // end of if v marked visited
    else {
        mark v visited
        switch(l(q)) {
            case (p ∈ Φp):
                switch(sign(v)) {
                    case("+"): if s is a sub-state and l(q) ∉ L'(s) return false
                    case("-"): if s is a sub-state and ¬l(q) ∉ L'(s) return false
                    case("neutral"): return false
                } // end of switch(sign(v))
            case(∧):
                if s is a leaf return false
                else
                    switch(sign(v)) {
                        case(neutral): for all v'' ∈ {v' / v →B⊗ v'}
                            if not DFS(v'') return false
                        case("+"): for all v'' ∈ {v' / v →B⊗ v'}
                            if not DFS(v'') return false
                        case("-"): for all v'' ∈ {v' / v →B⊗ v'}
                            if DFS(v'') return true else return false
                    } // end of switch(sign (v))
            case(∨):
                if s is a leaf return false
                else
                    switch(sign(v)) {
                        case(neutral): for all v'' ∈ {v' / v →B⊗ v'}
                            if DFS(v'') return true else return false
                        case("+"): for all v'' ∈ {v' / v →B⊗ v'}
                            if DFS(v'') return true else return false
                        case("-"): for all v'' ∈ {v' / v →B⊗ v'}
                            if not DFS(v'') return false
                    } // end of switch(sign (v))
            case(<•>):
                if s is a leaf return true
                else for the v'' ∈ {v' / v →B⊗ v'} if not DFS(v'') return false
            case(X†, PCAg, ACAg, <=⇒, ?):
                if s is a leaf return false
                else for the v'' ∈ {v' / v →B⊗ v'} if not DFS(v'') return false
        } // end of switch(l(q))
    } // end of else
    return true }

```

---

**Figure 8.** Model checking algorithm

### Case Study

To show how the model checking technique works, let us consider the following case study. The idea is to check if the dialogue game protocol specified in Section 4.1 and illustrated by Figure 5 satisfied the following property explained in Section 4.2:

$$\begin{aligned} AG^+(Challenge(Ag_2, PC(Ag_1, Ag_2, t, \phi))) \Rightarrow \\ F^+Justify(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi)) \end{aligned}$$

In order to simplify this formula, we use *Ch* for *Challenge* and *Jus* for *Justify*. The tableau of this formula is illustrated by Figure 9. The associated ABTA of this formula is given by Figure 10. This formula is equivalent to:

$$AG^+(\neg Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \vee F^+Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi)))$$

The first rule we can apply is *R6* labeled by " $\neg$ ". We obtain then the formula (2) of Figure 9. From this formula we obtain the formula  $\Phi$  that we consider in order to compute the acceptance states:

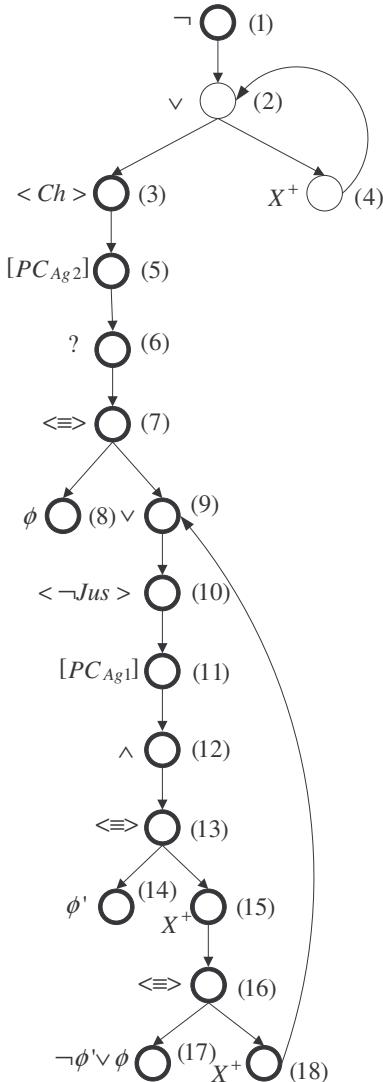
$$\Phi = F^+(Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$$

In the ABTA of Figure 10 state (1) and states from (3) to (18) are the acceptance states according to Definition 6. States (2) and (4) are not acceptance states. Because only the first state is labeled by  $\neg$ , all finite and infinite paths are negative paths. Consequently, the only infinite path that is a valid proof of the formula  $\Phi$  is (1, (2, 4)\*). In this path there is no acceptance state that occurs infinitely often. Therefore, this path satisfies the Büchi condition. The path visiting the state (3) and infinitely often the state (9) does not satisfy the formula because there is a challenge action (state (3)), and globally no justification action of the content of the challenged propositional commitment (state (9)).

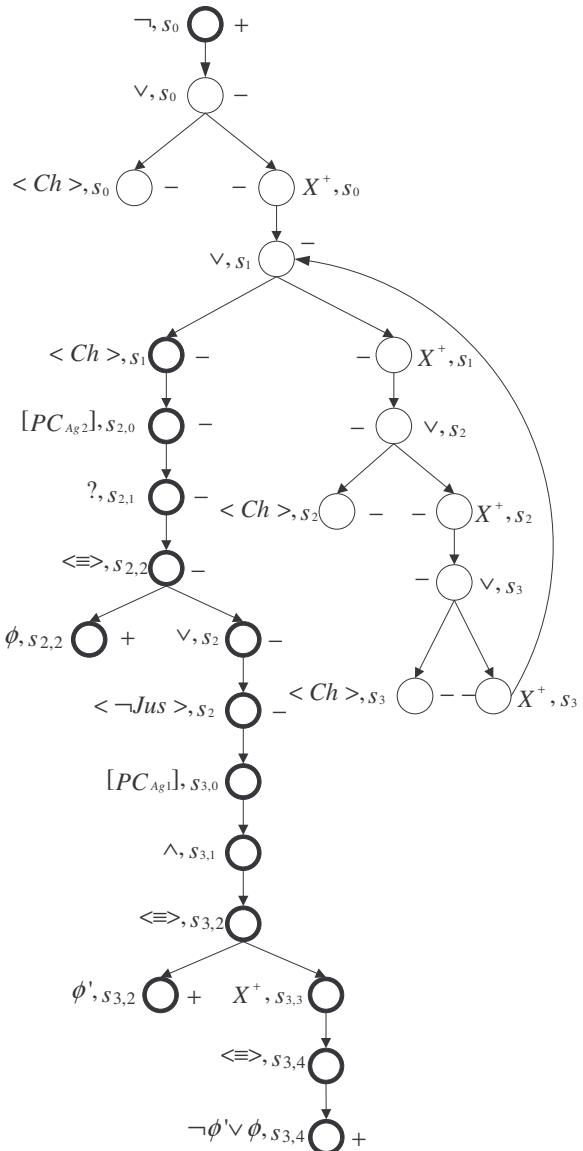
Figure 11 illustrates the automaton  $B_{\otimes}$  resulting from the product of the transition system of Figure 5 (noted TS[5]) and the ABTA of Figure 10 (noted ABTA[10]). In order to check if the language of this automaton is empty, we check if there is a successful run. The idea is to verify if  $B_{\otimes}$  contains an infinite path visiting the state (3) and infinitely often the state (9) of ABTA[10]. If such a path exists, then we conclude that the formula is not satisfied by TS[5]. Indeed, the only infinite path of  $B_{\otimes}$  is successful because it does not touch any accepted state and all leaves are also successful. For instance, the leaf labeled by  $(Ch, s_0)$  is successful since there is no state  $s_i$  such that  $s_0 \xrightarrow{Ch} s_i$ . The leaf labeled by  $(\neg\phi' \vee \phi, s_{3,4})$  is successful because it is a positive leaf and  $s_{3,4} \models \neg\phi' \vee \phi$ . Therefore, TS[5] is accepted by ABTA[10]. Consequently, TS[5] satisfies the formula and respects the structure of challenge and justification actions.

$\neg : AG^+(\neg Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \vee F^+ Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi)))$ (1)	
$\vee : EF^+(Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi'))))$ (2)	
$< Ch > : E(Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi'))))$ (3)	$< X^+ > : EX^+(F^+(Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi')))))$ (4)
$[PC_{Ag2}] : E(PC(Ag_2, Ag_1, t, ?\phi) \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi'))))$ (5)	$E(F^+(Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi')))))$ (2)
$? : E((? \phi) \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi'))))$ (6)	
$\Leftrightarrow : E(\phi \wedge G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi'))))$ (7)	
$\phi$ (8) $\vee : E(G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (9)	
$\neg \neg Jus : E(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi)), X^+ G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (10)	
$[PC_{Ag1}] : E(PC(Ag_1, Ag_2, t, \phi' \therefore \phi), X^+ G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (11)	
$\wedge : E(\phi' \therefore \phi, X^+ G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (12)	
$\Leftrightarrow : E(\phi', X^+(\neg \phi \vee \phi), X^+ G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (13)	
$\phi'$ (14) $X^+ : E(X^+(\neg \phi \vee \phi), X^+ G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (15)	
$\Leftrightarrow : E((\neg \phi \vee \phi), X^+ G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (16)	
$\neg \phi \vee \phi$ (17) $X^+ : E(X^+ G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (18)	
$E(G^+(\neg Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi))))$ (9)	

**Figure 9.** The tableau for  
 $AG^+(Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \Rightarrow F^+ Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi' \therefore \phi)))$



**Figure 10.** The ABTA for The formula  
 $AG^+(Ch(Ag_2, PC(Ag_1, Ag_2, t, \phi)) \Rightarrow F^+Jus(Ag_1, PC(Ag_1, Ag_2, t, \phi'.; \phi)))$

**Figure 11.** The ABTA product graph

## 6. Termination and Computational Complexity

In this section, we prove the termination of the translation procedure and we discuss the worst-case time complexity of our model checking<sup>3</sup>. Since the translation procedure is based on tableau rules, we need to prove the finiteness of the tableau. The methodology we follow is inspired by [18,21].

If  $\sigma_2$  is a CTL\*<sup>CA</sup> formula resulting from the application of a rule to a CTL\*<sup>CA</sup> formula  $\sigma_1$ , then we say that  $\sigma_2$  is a child of  $\sigma_1$  in the tableau and  $\sigma_1$  is the parent of  $\sigma_2$ . The *height* of a tableau [18] is defined as the length of the longest sequence  $\langle \sigma_0, \sigma_1, \dots \rangle$ , where  $\sigma_i$  is the parent of  $\sigma_{i+1}$ . To prove the finiteness of a tableau, we will establish that each formula has a maximum height tableau.

Intuitively, to show the finiteness of the tableau, we will define a strict ordering relation  $\prec$  between CTL\*<sup>CA</sup> formulae and then show that: **1)** if  $\sigma_1$  is the parent of  $\sigma_2$ , then  $\sigma_1 \prec \sigma_2$ ; **2)** the strict ordering relation  $\prec$  has no infinite ascending chains.

The ordering relation  $\prec$  should reflect the fact that applying tableau rules results in shorter formulae or recursive formulae. The idea is to prove that the number of nodes of the ABTA is finite. Therefore, the definition of this ordering is based either on the fact that formulae are recursive or on the length of formulae. We notice that in the case of recursive formulae, we obtain cycles which are infinite paths on a finite number of nodes. The length of a formula is defined inductively as follows:

**Definition 7** *The length of a formula  $\psi$  denoted by  $|\psi|$  is the number of variables and operators in  $\psi$  i.e.:*

$$\begin{aligned}
|\psi| &= 1 \text{ if } \psi \text{ is an atomic formula} \\
|\neg\psi| &= 1 + |\psi| \\
|\psi_1 \wedge \psi_2| &= 1 + |\psi_1| + |\psi_2| \\
|\psi_1 \vee \psi_2| &= 1 + |\psi_1| + |\psi_2| \\
|? \psi| &= 1 + |\psi| \\
|\psi_1 \therefore \psi_2| &= 1 + |\psi_1| + |X^+(\neg\psi_1 \vee \psi_2)| \\
|X \psi| &= 1 + |\psi| \text{ where } X \in \{X^+, X^-\} \\
|\psi_1 \cup \psi_2| &= 1 + |\psi_1| + |\psi_2| \text{ where } (U, X) \in \{(U^+, X^+), (U^-, X^-)\} \\
|PC(Ag_1, Ag_2, t, \psi)| &= 1 + |\psi| \\
|C(Ag_1, SC(Ag_1, Ag_2, t, \psi))| &= 1 + |PC(Ag_1, Ag_2, t, \psi)| \\
|Withdraw(Ag_1, PC(Ag_1, Ag_2, t, \psi))| &= 1 + |\neg PC(Ag_1, Ag_2, t, \psi)| \\
|Satisfy(Ag_1, PC(Ag_1, Ag_2, t, \psi))| &= 1 + |\psi| \\
|Violate(Ag_1, PC(Ag_1, Ag_2, t, \psi))| &= 1 + |\neg\psi| \\
|Reactivate(Ag_1, PC(Ag_1, Ag_2, t, \psi))| &= 1 + |PC(Ag_1, Ag_2, t, \psi)| \\
|Challenge(Ag_2, PC(Ag_1, Ag_2, t, \psi))| &= 1 + |PC(Ag_2, Ag_1, t', ?\psi)| \\
|Accept(Ag_2, SC(Ag_1, Ag_2, t, \psi))| &= 1 + |PC(Ag_2, Ag_1, t', \psi)| \\
|Refuse(Ag_2, SC(Ag_1, Ag_2, t, \psi))| &= 1 + |PC(Ag_2, Ag_1, t', \neg\psi)| \\
|Justify(Ag_1, PC(Ag_1, Ag_2, t, \psi' \therefore \psi))| &= 1 + |PC(Ag_1, Ag_2, t', \psi' \therefore \psi)| \\
|Attack(Ag_2, PC(Ag_1, Ag_2, t, \psi' \therefore \psi))| &= 1 + |PC(Ag_2, Ag_1, t', \psi' \therefore \neg\psi)|
\end{aligned}$$

<sup>3</sup> All the proofs of this section are available at:  
<http://users.encs.concordia.ca/~bentahar/SoMet2007-Appendix.pdf>

$$|Defend(Ag_1, PC(Ag_1, Ag_2, t, \psi' \therefore \psi))| = 1 + |PC(Ag_1, Ag_2, t', \psi' \therefore \psi)|$$

The ordering relation  $\prec$  is defined as follows:

**Definition 8** Let  $\sigma_1 = E(\psi_1)$  and  $\sigma_2 = E(\psi_2)$  be two CTL\*<sup>CA</sup> formulae. Then,  $\sigma_1 \prec \sigma_2$  holds if

- 1-  $\sigma_1 \leqslant \sigma_2$
  - 2-  $\sigma_1 \not\leqslant \sigma_2$  and  $|\psi_1| > |\psi_2|$ .
- where  $\sigma_1 \leqslant \sigma_2$  iff  $X\psi_1$  appears in  $\psi_2$

The first clause is used when we have a recursive formula (this means that an *until* formula).  $\prec$  is irreflexive, asymmetric and transitive. The proof is straightforward from the definition since  $>$  and  $\leqslant$  are strict ordering relations.

In what follows, the notation  $\sigma_1 \rightarrow_R \sigma_2$  means that  $\sigma_1$  is the parent of  $\sigma_2$  using a tableau rule  $R$ . We have the following lemma (see the proof in the appendix<sup>4</sup>):

**Lemma 1** Let  $\sigma_1 = E(\psi_1)$  and  $\sigma_2 = E(\psi_2)$  be two DCTL\*<sub>CAN</sub> formulae. Then:

$$\sigma_1 \rightarrow_R \sigma_2 \Rightarrow \sigma_1 \prec \sigma_2.$$

To show that the ordering relation has no infinite ascending chains, we use the notion of Fischer-Ladner closure of a formula  $\psi$  ( $CL(\psi)$ ) [22]. The idea underlying the definition of this notion is to prove that if a tableau has a root  $\psi$ , then all formulae  $\psi'$  of this tableau have a formula in  $CL(\psi)$  (i.e.  $\psi' \in CL(\psi)$ ). Furthermore, if we prove that  $CL(\psi)$  is a finite set, then we conclude that each formula appearing in a given tableau belongs to a finite set. This result will be very helpful to prove that the ordering relation  $\prec$  has no infinite ascending chains.

**Definition 9** Let  $\psi$  be a CTL\*<sup>CA</sup> formula. The Fischer-Ladner closure of  $\psi$ ,  $CL(\psi)$  is the smallest set such that the following hold:

- If  $\psi$  is an atomic formula then  $\{\psi\} \subseteq CL(\psi)$
- If  $\psi = \neg\psi_1$  then  $CL(\psi_1) \subseteq CL(\psi)$  and  $\{\neg\psi_1\} \subseteq CL(\psi)$
- If  $\psi = \psi_1 \wedge \psi_2$  then  $CL(\psi_1) \subseteq CL(\psi)$  and  $CL(\psi_2) \subseteq CL(\psi)$  and  $\{\psi_1 \wedge \psi_2\} \subseteq CL(\psi)$
- If  $\psi = \psi_1 \vee \psi_2$  then  $CL(\psi_1) \subseteq CL(\psi)$  and  $CL(\psi_2) \subseteq CL(\psi)$  and  $\{\psi_1 \vee \psi_2\} \subseteq CL(\psi)$
- If  $\psi = ?\psi_1$  then  $CL(\psi_1) \subseteq CL(\psi)$  and  $\{?\psi_1\} \subseteq CL(\psi)$
- If  $\psi = \psi_1 \therefore \psi_2$  then
  - $CL(\psi_1) \subseteq CL(\psi)$  and  $CL(X^+(\neg\psi_1 \vee \psi_2)) \subseteq CL(\psi)$  and  $\{\psi_1 \therefore \psi_2\} \subseteq CL(\psi)$
  - If  $\psi = X\psi_1$  then  $CL(\psi_1) \subseteq CL(\psi)$  and  $\{X\psi_1\} \subseteq CL(\psi)$  where  $X \in \{X^+, X^-\}$
  - If  $\psi = \psi_1 U \psi_2$  then
    - $CL(\psi_1) \subseteq CL(\psi)$  and  $CL(\psi_2) \subseteq CL(\psi)$  and  $CL(X(\psi_1 U \psi_2)) \subseteq CL(\psi)$
    - and  $\{\psi_1 U \psi_2\} \subseteq CL(\psi)$  where  $(U, X) \in \{(U^+, X^+), (U^-, X^-)\}$
- If  $\psi = PC(Ag_1, Ag_2, t, \psi_1)$  then  $CL(\psi_1) \subseteq CL(\psi)$  and  $\{PC(Ag_1, Ag_2, t, \psi_1)\} \subseteq CL(\psi)$

<sup>4</sup> <http://users.encs.concordia.ca/~bentahar/SoMet2007-Appendix.pdf>

If  $\psi = C(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(PC(Ag_1, Ag_2, t, \psi_i)) \subseteq CL(\psi)$  and  $\{C(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Withdraw(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(\neg PC(Ag_1, Ag_2, t, \psi_i)) \subseteq CL(\psi)$  and  
 $\{Withdraw(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Satisfy(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(\psi_i) \subseteq CL(\psi)$  and  $\{Satisfy(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Violate(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(\neg \psi_i) \subseteq CL(\psi)$  and  $\{Violate(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Reactivate(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(PC(Ag_1, Ag_2, t, \psi_i)) \subseteq CL(\psi)$  and  
 $\{Reactivate(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Challenge(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(PC(Ag_1, Ag_2, t', ?\psi_i)) \subseteq CL(\psi)$   
and  $\{Challenge(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Accept(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(PC(Ag_1, Ag_2, t', \psi_i)) \subseteq CL(\psi)$   
and  $\{Accept(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Refuse(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))$  then  
 $CL(PC(Ag_1, Ag_2, t', \neg \psi_i)) \subseteq CL(\psi)$   
and  $\{Refuse(Ag_1, PC(Ag_1, Ag_2, t, \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Justify(Ag_1, PC(Ag_1, Ag_2, t, \psi_2 \therefore \psi_i))$  then  
 $CL(PC(Ag_1, Ag_2, t', \psi_2 \therefore \psi_i)) \subseteq CL(\psi)$   
and  $\{Justify(Ag_1, PC(Ag_1, Ag_2, t, \psi_2 \therefore \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Attack(Ag_2, PC(Ag_1, Ag_2, t, \psi_2 \therefore \neg \psi_i))$  then  
 $CL(PC(Ag_2, Ag_1, t', \psi_2 \therefore \neg \psi_i)) \subseteq CL(\psi)$   
and  $\{Attack(Ag_2, PC(Ag_1, Ag_2, t, \psi_2 \therefore \neg \psi_i))\} \subseteq CL(\psi)$

If  $\psi = Defend(Ag_1, PC(Ag_1, Ag_2, t, \psi_2 \therefore \psi_i))$  then  
 $CL(PC(Ag_1, Ag_2, t', \psi_2 \therefore \psi_i)) \subseteq CL(\psi)$   
and  $\{Defend(Ag_1, PC(Ag_1, Ag_2, t, \psi_2 \therefore \psi_i))\} \subseteq CL(\psi)$

**Lemma 2** Let  $\psi$  be a formula, then  $CL(\psi)$  is finite and bounded in size by  $2|\psi|$ .

The next lemma establishes the link between tableau rules and Fischer-Ladner closure of formulae.

**Lemma 3** Let  $\sigma_1 = E(\Phi, \psi_1)$  and  $\sigma_2 = E(\Phi, \psi_2)$  be two CTL\*<sup>CA</sup> formulae. Then:  
 $\sigma_1 \rightarrow_R \sigma_2 \Rightarrow CL(\psi_2) \subseteq CL(\psi_1)$ .

Intuitively,  $\sigma_i \prec \sigma_j$  holds if  $\sigma_i$  is an ancestor of  $\sigma_j$  in some tableau, i.e. if there are rules  $Ri, \dots, Rj$  such that:  $\sigma_i \rightarrow_{Ri} \sigma_{i+1} \dots \rightarrow_{Rj} \sigma_j$ . We have the following lemma:

**Lemma 4** The ordering relation  $\prec$  has no infinite ascending chains.

Now, we can easily prove the finiteness theorem.

**Theorem 2 (Termination)** *For any  $CTL^{*CA}$  formula  $\sigma_l$ , there is a maximum height tableau has  $\sigma_l$  as a root.*

Let us now discuss the worst-case time complexity of our model checking (see the proofs in the appendix<sup>5</sup>).

**Lemma 5** *Let  $\psi$  be a  $CTL^{*CA}$  formula, and let  $B_\psi = \langle Q, l, \rightarrow, q_0, F \rangle$  be the ABTA obtained by the translation procedure. Then  $|B_\psi| < 2^{|\psi|}$ .*

The complexity of the transition procedure is thus exponential in the size of the formula ( $O(2^{|\psi|})$ ). However, if  $\psi$  is a  $CTL^{CA}$  formula,  $|B_\psi|$  is bounded by  $|\psi|$ . The complexity is then linear in the size of the formula. This result follows from the fact that in  $CTL^{CA}$  we have only state formulae.

**Lemma 6** *Let  $T = \langle S, Lab, \wp, L, Act, \rightarrow, s_0 \rangle$  be a transition system for a dialogue game, and let  $B_\psi = \langle Q, l, \rightarrow, q_0, F \rangle$  be an ABTA for  $\psi$ . The time complexity of the model checking algorithm is bounded by  $|T| \times |B_\psi|$  where  $|T| = |S| + |\wp| + |\rightarrow|$  and  $|\wp|$  is the number of sub-states in all structure transition systems of  $T$ .*

The worst-case time complexity of our model checking technique is therefore linear in the size of the model and exponential in the size of the formula to be checked.

## 7. Conclusion

In this paper, we have addressed the verification problem of communicating agent-based systems, in which knowledge-driven agents communicate by reasoning about dialogue game protocols. We proposed a new model checking technique allowing for the verification of both the correctness of the protocols and the agents' compliance to the structure of the communicative acts. This technique uses a combination of an automata-based and a tableau-driven algorithm to verify temporal and action specification. The formal properties to be verified are expressed in  $CTL^{*CA}$  logic and translated to ABTA using tableau rules. We proved that this model checking algorithm working on a product graph is an efficient on-the-fly procedure that always terminates.

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<sup>5</sup> <http://users.encs.concordia.ca/~bentahar/SoMet2007-Appendix.pdf>

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