# Real-Time Conditional Commitment Logic

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**Abstract.** A considerably large class of multi-agent systems (MASs) employed in real-time environments requires the possibility to express time-critical properties. In this paper, we develop a system of temporal logic RTCTL$^{cc}$, an extension of CTL modalities and interval bound until modalities with conditional commitment and their fulfillment modalities. This logic allows us to formally model the interaction among autonomous agents using conditional commitments and to combine qualitative temporal aspects together with real-time constraints (time instants or intervals) in order to permit reasoning about qualitative and quantitative requirements and their specifications. We point out that useful properties of MASs, which are required to express temporal constraints as a fundamental part of functional requirements can be expressed in RTCTL$^{cc}$. We also argue that time-critical properties expressed in executable action languages in other contributed approaches can be expressed in RTCTL$^{cc}$.

**Keywords:** Multi-Agent Systems · Real-time · Conditional commitments · Qualitative and quantitative requirements

## 1 Introduction

Social and objective commitments among pairs of interacting agents within multi-agent systems (MASs) have been acknowledged as a powerful engineering tool to represent, model, and reason about the content of multi-agent interactions [2,9]. They also provide a fundamental basis for addressing the challenge of checking and validating the compliance of autonomous agents' behaviors with preset specifications [3,8,12]. Temporal logics, such as LTL [16], CTL [3,6,8,12], and CTL* [11] have been successfully extended with temporal modalities to represent and reason about social commitments and some of related commitment actions. What makes commitment languages special is that they include modalities needed for modeling interaction among agents, which cannot be expressed


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in pure temporal logics. All commitment languages, however, have paid more heed to deal with qualitative temporal commitment properties used to check the correctness of commitment protocols [8,10,12] and business models having social semantics [7,17]. With these specification languages, we can express qualitative commitment properties such as whenever the customer accepts the offer, the merchant conditionally commits to eventually deliver goods provided that the customer sends the payment. This property obviously places no bound constraint on the time that might elapse before the delivery of goods.

Although qualitative properties are in principle desirable to express various formal specifications (e.g., safety and liveness properties [11]), there is a considerably large class of MASs employed in real-time environments. The class requires the possibility to express time-critical properties. Such properties indeed express the occurrences of events at time instants or within time intervals, and play an essential role in verifying the correctness of systems' specifications. The most utilized timing constraint is deadline, i.e., the time instant before which the required result must be actually delivered. Consider the following examples to clarify quantitative properties that are important and relevant in real and practical systems, but ignored in temporal commitment logics. In a business protocol, we might need to affirm a quantitative correctness property such as once the payment is received, the merchant must commit to deliver goods to the customer within bounded time, for instance, 2 time units (days) during which only a certain set of preparation steps is performed. In the car rental business scenario discussed in [4], a customer needs first to sign a contract with a car rental agency. The customer is accordingly obliged to return back the car at a certain bounded time, namely, 5 days from the day of signing the rental contract. In a typical service-level agreement, there is a commitment to maintain network connectivity during bounded times (e.g., at Concordia university, the IT department performs the maintenance process every last Friday in each month).

The current **research questions** are: 1) how temporal deadline constraints can be modeled in the commitment logical languages? 2) how can we define unbounded modalities from bounded ones? and 3) how can we express qualitative and quantitative properties using the same specification commitment logical language? The **contribution** of the paper is the development of an expressive logical language called RTCTL$^{cc}$ that allows us to address these research questions. RTCTL$^{cc}$ particularly extends our CTL$^{cc}$ (CTL plus conditional commitments and their fulfillment modalities [6]) with quantitative modalities in a systematic fashion. We adopt CTL$^{cc}$ as the semantics of conditional commitments and their fulfillment achieve all operational semantic rules commonly agreed on in the literature and meet all Singh's reasoning postulates [16], as shown in [6]. We in fact follow Emerson et al.'s methodology to develop a real-time CTL logic (RTCTL) to deal with different sorts of real-time applications [13].

This work continues as follows. In Section 2, we present the extended version of the interpreted system formalism introduced in our previous work [3,8] and define the syntax and semantics of RTCTL$^{cc}$. In Section 3, we discuss the related work. We conclude and identify future research directions in Section 4.

## 2 Extended Version of Interpreted Systems and RTCTL$^{cc}$

The formalism of interpreted systems [14] provides a very popular framework to model MASs. In [3,6,8], we extended this formalism with sets of shared and unshared variables to account for agent communication. Specifically, the extended version of interpreted systems is composed of a set $\mathcal{A} = \{1, \ldots, n\}$ of $n$ agents plus the environment agent $e$. Each agent $i \in \mathcal{A}$ is characterized by:

1. $L_i$ is a finite set of local states. Each local state $l_i$ represents the whole information about the system that the agent has at a given moment.
2. $Var_i$ is a set of at most $n-1$ local variables (i.e., $|Var_i| \leq n-1$) to model communication channels through which values are sent and received.
3. $Act_i$ is a finite set of local actions available to the agent including the *null* action in order to account for the temporal evolution of the system.
4. $\mathcal{P}_i : L_i \rightarrow 2^{Act_i}$ is a local protocol function, producing the set of enabled actions that might be performed by $i$ in a given local state.
5. $\iota_i \subseteq L_i$ is the set of initial states of the agent $i$.
6. $\tau_i : L_i \times Act_1 \times \ldots \times Act_n \times Act_e \rightarrow L_i$ is a local transition function, defining a local state from another local state and a joint action $a = (a_1, \ldots, a_n, a_e)$, one for each agent and environment agent.

The environment agent $e$, which captures the information that might not pertain to a specific agent, is characterized by $L_e, Var_e, Act_e, \mathcal{P}_e, \iota_e$ and $\tau_e$. The notion of social state (termed global state in [14]) represents the screenshot of all agents in the system at a certain moment. A social state $s \in S$ is a tuple $s = (l_1, \ldots, l_n, l_e)$ where each element $l_i \in L_i$ represents the $i$'s local state along with the environment state $l_e$. The set of all social states $S \subseteq L_1 \times \ldots \times L_n \times L_e$ is a subset of the Cartesian product of all local states of all agents and the environment agent. All local transition functions are combined together to define a social transition function $\tau : S \times Act_1 \times \ldots \times Act_n \times Act_e \rightarrow S$ in order to give the overall transition function for the system. Let $l_i(s)$ denotes the local state of agent $i$ in the social state $s$ and the value of a variable $x$ in the set $Var_i$ at $l_i(s)$ is denoted by $l_i^x(s)$. A communication channel between $i$ and $j$ does exist iff $Var_i \cap Var_j \neq \emptyset$. For the variable $x \in Var_i \cap Var_j$, $l_i^x(s) = l_j^x(s')$ means the values of $x$ in $l_i(s)$ for $i$ and in $l_j(s')$ for $j$ are the same. Finally, the valuation function $\mathcal{V} : \mathcal{PV} \rightarrow 2^S$ defines what atomic propositions are true from the set $\mathcal{PV}$ at system states. To summarize, the extended version of the interpreted system formalism is given by the following tuple $IS^+ = \big(\{L_i, Var_i, Act_i, \mathcal{P}_i, \tau_i, \iota_i\}_{i \in \mathcal{A}}, \{L_e, Var_e, Act_e, \mathcal{P}_e, \tau_e, \iota_e\}, \mathcal{V}\big)$.

**Definition 1 (RTCTL$^{cc}$ models, adopted from [6]).** *A conditional commitment model* $M = \big(S, I, T, \{\sim_{i\rightarrow j} \mid (i,j) \in \mathcal{A}^2\}, \mathcal{V}\big)$ *is generated from* $IS^+ = \big(\{L_i, Var_i, Act_i, \mathcal{P}_i, \tau_i,\ \iota_i\}_{i \in \mathcal{A}}, \{L_e, Act_e, \mathcal{P}_e, \tau_e, \iota_e\}, \mathcal{V}\big)$ *by synchronising joint actions of* $n+1$ *composed agent models as follows:*

- $S \subseteq L_1 \times \ldots \times L_n \times L_e$ *is a set of reachable social states for the system.*
- $I \subseteq \iota_1 \times \ldots \times \iota_n \times \iota_e$ *is a set of initial states for the system such that* $I \subseteq S$.

- *$T \subseteq S \times S$ is a total temporal relation (i.e., each state has at least one successor) defined by $(s, s') \in T$ iff there exists a joint action $(a_1, \ldots, a_n, a_e) \in ACT = Act_1 \times \ldots \times Act_n \times Act_e$ such that $\tau(s, a_1, \ldots, a_n, a_e) = s'$.*
- *$\sim_{i \to j} \subseteq S \times S$ is a social accessibility relation defined for each pair $(i, j) \in \mathcal{A}^2$ by $s \sim_{i \to j} s'$ iff the following conditions hold: 1) $l_i(s) = l_i(s')$; 2) $(s, s') \in T$; 3) $Var_i \cap Var_j \neq \emptyset$ and $\forall x \in Var_i \cap Var_j$ we have $l_i^x(s) = l_j^x(s')$; and 4) $\forall y \in Var_j - Var_i$ we have $l_j^y(s) = l_j^y(s')$.*
- *$\mathcal{V} : \mathcal{PV} \to 2^S$ is a valuation function defined as in $IS^+$.*

Following Emerson et al. [13], each transition in our quantitative temporal model $M$ takes a single time unit for execution from one state to another state. The underlying real-time model is discrete and has a tree-like structure. The model $M$ is unwound into a set of execution paths in which each path $\pi = s_0, s_1, \ldots$ is an infinite sequence of social states increasing simultaneously over time such that $s_i \in S$ and $(s_i, s_{i+1}) \in T$ for each $i \geq 0$. $\pi(k)$ is the $k$-th state of the path $\pi$. The set of all paths starting at $s$ is denoted by $\Pi(s)$.

**Definition 2 (Syntax of RTCTL$^{cc}$ ).** *The syntax of RTCTL$^{cc}$ is as follows:*

$$\begin{aligned} \varphi ::= \; & p \mid \neg\varphi \mid \varphi \vee \varphi \mid EX\varphi \mid EG\varphi \mid E(\varphi \; U \; \varphi) \mid E(\varphi \; U^{[m..n]} \; \varphi) \\ & \mid A(\varphi \; U^{[m..n]} \; \varphi) \mid CC \mid Fu \\ CC ::= \; & WCC(i, j, \varphi, \varphi) \mid SCC(i, j, \varphi, \varphi) \\ Fu ::= \; & FuW(i, WCC(i, j, \varphi, \varphi)) \mid FuS(i, SCC(i, j, \varphi, \varphi)) \end{aligned}$$

*where:*

- *$p \in \mathcal{PV}$ is an atomic proposition. $\neg$ and $\vee$ are the usual Boolean connectives.*
- *$E$ and $A$ are the existential and universal quantifiers on paths.*
- *$X$, $G$ and $U$ are CTL path modal connectives standing for "next", "globally", and "until", respectively.*
- *$m$ and $n \in \mathbb{N}^+$ are natural numbers denoting the bounds of time intervals.*
- *$U^{[m..n]}$ stands for interval bound until. This operator is used to abbreviate other bounded operators (e.g., $F^{[m..n]}$, $U^{\leq n}$ and $U^{=n}$, see Table 1).*
- *$i$ and $j \in \mathcal{A}$ are two agents. $WCC$, $SCC$, $FuW$ and $FuS$ stand for weak and strong conditional commitment and their fulfillments, respectively [6].*

From these syntactical rules, the formula $EX\varphi$ is read as "there exists a path such that at the next state of the path $\varphi$ holds", $EG\varphi$ is read as "there exists a path such that $\varphi$ holds globally along the path", and $E(\varphi \; U \; \psi)$ is read as "there exists a path such that $\psi$ eventually holds and $\varphi$ continuously holds until then". $E(\varphi \; U^{[m..n]} \; \psi)$ (respectively, $A(\varphi \; U^{[m..n]} \; \psi)$) can be read as "there exists a path such that (respectively, for all paths) $\psi$ eventually holds at time instant $i$ within the interval $[m..n]$ and $\varphi$ continuously holds from $m$ until then". We introduce the formula $A(\varphi \; U^{[m..n]} \; \psi)$ in the syntax of RTCTL$^{cc}$ because the equivalent one from $E$ is not compact and depends on other three operators (see Table 1).

The formula $WCC(i, j, \psi, \varphi)$ (respectively, $SCC(i, j, \psi, \varphi)$) is read as "agent $i$ weakly (respectively, strongly) commits towards agent $j$ to consequently satisfy $\varphi$ once the antecedent $\psi$ holds". Intuitively, weak commitments can be activated even if the antecedent will never be satisfied, while strong commitments are solely established when there is a possibility to satisfy their antecedents. The commitment antecedents and consequences can be quantitative and/or qualitative formulae. The formula $FuW(i, WCC(i, j, \psi, \varphi))$ (respectively, $FuS(i, SCC(i, j, \psi, \varphi)))$ is read as "the weak (respectively, strong) conditional commitment $WCC(i, j, \psi, \varphi)$ (respectively, $SCC(i, j, \psi, \varphi)$) is fulfilled".

**Definition 3 (Semantics of RTCTL$^{cc}$).** *Given the model $M$, the satisfaction of RTCTL$^{cc}$ formula $\varphi$ in a state $s$, denoted by $(M, s) \models \varphi$, is recursively defined as follows:*

- $(M, s) \models p$ *iff* $s \in \mathcal{V}(p)$,
- $(M, s) \models \neg\varphi$ *iff* $(M, s) \not\models \varphi$,
- $(M, s) \models \varphi \vee \varphi$ *iff* $(M, s) \models \varphi$ *or* $(M, s) \models \varphi$,
- $(M, s) \models EX\varphi$ *iff* $\exists \pi \in \Pi(s)$ *such that* $(M, \pi(1)) \models \varphi$,
- $(M, s) \models EG\varphi$ *iff* $\exists \pi \in \Pi(s)$ *such that* $\forall k \geq 0, (M, \pi(k)) \models \varphi$,
- $(M, s) \models E(\varphi\ U\ \psi)$ *iff* $\exists \pi \in \Pi(s)$ *such that* $\exists k \geq 0,\ (M, \pi(k)) \models \psi$ *and* $\forall j, 0 \leq j < k, (M, \pi(j)) \models \varphi$,
- $(M, s) \models E(\varphi\ U^{[m..n]}\ \psi)$ *iff* $\exists \pi \in \Pi(s)$ *such that* $\exists i, m \leq i \leq n,\ (M, \pi(i)) \models \psi$ *and* $\forall j, m \leq j < i, (M, \pi(j)) \models \varphi$,
- $(M, s) \models A(\varphi\ U^{[m..n]}\ \psi)$ *iff* $\forall \pi \in \Pi(s)$ *such that* $\exists i, m \leq i \leq n,\ (M, \pi(i)) \models \psi$ *and* $\forall j, m \leq j < i, (M, \pi(j)) \models \varphi$,
- $(M, s) \models WCC(i, j, \psi, \varphi)$ *iff* $\forall s' \in S$ *such that* $s \sim_{i \to j} s'$ *and* $(M, s') \models \psi$, $(M, s') \models \varphi$,
- $(M, s) \models SCC(i, j, \psi, \varphi)$ *iff* (1) $\exists s' \in S$ *such that* $s \sim_{i \to j} s'$ *and* $(M, s') \models \psi$, *and* (2) $(M, s) \models WCC(i, j, \psi, \varphi)$,
- $(M, s) \models FuW(i, WCC(i, j, \psi, \varphi))$ *iff* $\exists s' \in S$ *such that*$s' \sim_{i \to j} s$ *and* $(M, s') \models WCC(i, j, \psi, \varphi)$ *and* $(M, s) \models \varphi \wedge \neg WCC(i, j, \psi, \varphi)$,
- $(M, s) \models FuS(i, SCC(i, j, \psi, \varphi))$ *iff* $\exists s' \in S$ *such that*$s' \sim_{i \to j} s$ *and* $(M, s') \models SCC(i, j, \psi, \varphi)$ *and* $(M, s) \models \psi \wedge \neg SCC(i, j, \psi, \varphi)$.

With respect to the defined semantics, other propositional connectives can be abbreviated in terms of the above as usual: $\wedge$ for conjunction, $\Rightarrow$ for implication, $\equiv$ for equivalence, and $\top$ for constant true proposition. In Table 1, we define some qualitative and quantitative modalities. From the table, $k$ in the formula $E(\varphi\, U^{\leq k}\ \psi)$ reflects the "maximum number of permitted transitions along a path before the eventuality $\varphi\ U\ \psi$ holds" [13]. In this sense, $EF^{=k}\ \psi$ can be read as "there exists a path such that $\psi$ eventually holds exactly at $k$ time instant along the path". The pressing question is whether or not we can define unbounded modalities from the bounded ones? Following Emerson et al.'s strategy in [13], the unbounded modalities can be defined from the analogous bounded ones when the bounded time exists. For example, $A(\varphi\ U\ \psi) = \exists k \geq 0\ s.t.\ A(\varphi\ U^{\leq k}\ \psi)$. We conclude by illustrating how RTCTL$^{cc}$ can be utilized to express the properties that consider an explicit bound on the time instant.

*Example 1.* Let $q$=*receivePayment* and $p$=*deliverGoods* be two propositions, then the formula $AG(WCC(Mer, Cus, q, EF^{\leq 3} p))$ specifies that along all paths

**Table 1.** Some abbreviations of RTCTL$^{cc}$

| **Qualitative abbreviations** | **Quantitative abbreviations** |
|---|---|
| $EF\varphi \triangleq E(\top\ U\ \varphi)$ | $EF^{\leq k}\varphi \triangleq E(\top\ U^{\leq k}\ \varphi) \triangleq E(\top\ U^{[0..k]}\ \varphi)$ |
| $AG\varphi \triangleq \neg EF\neg\varphi$ | $EF^{[m..n]}\varphi \triangleq E(\top\ U^{[m..n]}\varphi)$ |
| $A(\varphi\ U\ \psi) \triangleq$ $\neg E(\neg\varphi\ U\ (\neg\psi \wedge \neg\varphi)) \wedge \neg EG\neg\varphi$ | $AF^{\leq k}\varphi \triangleq A(\top\ U^{\leq k}\ \varphi) \triangleq A(\top\ U^{[0..k]}\ \varphi)$ $AF^{[m..n]}\varphi \triangleq A(\top U^{[m..n]}\varphi)$ |
| $AF\varphi \triangleq A(\top\ U\ \varphi)$ | $EG^{\leq k}\varphi \triangleq \neg AF^{\leq k}\neg\varphi$ |
| $AX\varphi \triangleq \neg EX\neg\varphi$ | $EG^{[m..n]}\varphi \triangleq \neg AF^{[m..n]}\neg\varphi$ |
| | $AG^{\leq k}\varphi \triangleq \neg EF^{\leq k}\neg\varphi$ |
| | $AG^{[m..n]}\varphi \triangleq \neg EF^{[m..n]}\neg\varphi$ |
| | $E(\varphi\ U^{=k}\ \psi) \triangleq E(\varphi\ U^{[k..k]}\ \psi)$ |

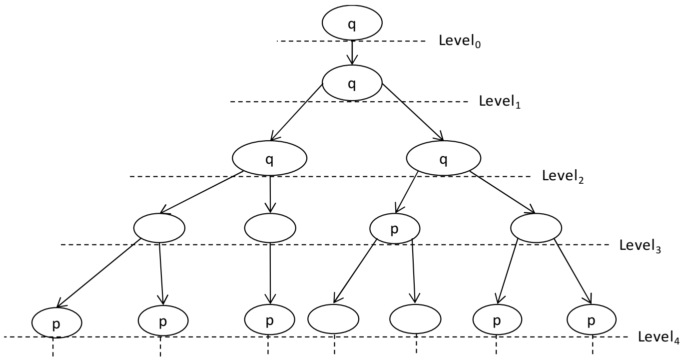


**Fig. 1.** shows an RTCTL$^{cc}$ model where the proposition $p$ holds at some future state of every possible path from $s_0$ to $s_4$ and the proposition q holds at all states in all paths from $s_0$ to $s_2$, formally, $(M, s_0) \models AF^{\leq 4}p \wedge AG^{\leq 2}q$.

the merchant globally commits to deliver goods to the customer within at most 3 days once she received the agreed payment.

*Example 2.* Consider the car rental scenario discussed in the introduction.

1. The formula $AG(SCC(Cus, Age, EF\ disposeCar, EF^{=5}\,returnBackCar))$ expresses that the customer is obliged to return back the rental car to the agency on exactly 5 days as soon as the rental contract is disposed.
2. The customer is obliged to pay the whole rental amount on the first three days of the rental period: $AG(SCC(Cus, Age, EF\ disposeCar, EF^{[1..3]}payment))$. After 2 days from disposing the rental car, the customer sends the agreed payment, which conducts the fulfillment of the commitment: $EF(FuS(Cus, SCC(Cus, Age, EF\ disposeCar, EF^{[1..3]}payment)))$.
3. The agency is committed to the customer to withdraw the broken car and reimburse the remaining days within 2 days from the end of the rental period as soon as the customer notifies for breaking down: $AG(SCC(Age, Cus, EF^{\leq 5}\,notifyBrokenCar, EF\ withdrawBrokenCar \wedge EF^{[5..7]}reimburse))$.

Other examples in the introduction can be formalized in a similar manner.

## 3 Related Work

There are only two logical approaches that have defined formal semantics for conditional commitments, a universal type of social commitments, in the literature. The first approach is the one introduced by Singh [16]. In this approach, the author extended LTL with two modalities to represent and reason about two different types of conditional commitments (practical and dialectical). In the second approach, we extended CTL with four modalities to represent and reason about two types of conditional commitments (weak and strong) and their fulfillments [6]. The semantic rules of weak conditional commitments function as the ones introduced in [16]. The resulting logical language is so-called $\text{CTL}^{cc}$. Since unconditional commitments can be treated as a special case of conditional commitments when the antecedent is true: $C(i,j,\varphi) \triangleq WCC(i,j,\top,\varphi) \triangleq SCC(i,j,\top,\varphi)$, we beneath discuss the current approaches that develop only temporal unconditional commitment logics. Among these approaches, El Menshawy et al. [10] developed CTLC, an extension of CTL with unconditional commitment modality. El Menshawy et al. [8] improved the definition of the accessibility relation introduced in [10] to have a new semantics for unconditional commitment and fulfillment modalities. The new logic is called $\text{CTLC}^{+}$. The authors in [11] developed a branching time temporal logic called $\text{ACTL}^{*c}$ by extending $\text{CTL}^{*}$ with temporal modalities to represent and reason about unconditional commitments and all related actions. The authors in [1] introduced a temporal logic called $\text{CTLKC}^{+}$, a combination of CTL modalities, knowledge modality and unconditional commitment modality. It is known that temporal logics are time-abstract with regard to the occurrence of events in the past and future without referencing to the precise timing of events. Therefore, temporal-logics-based approaches discussed above are not suitable to represent and reason about deadlines of commitments that incorporate metrics or real-time constraints as in real-life business scenarios. The current approach extends $\text{CTL}^{cc}$ with real-time constraints in the bounded operators to rigorously address this limitation.

Mallya et al. [15] enriched CTL with: predicates to reason about commitments and fulfillment and violation actions; and two existential and universal quantifiers to capture temporal deadlines in the commitment consequences. Our interval bound until operators along with existential and universal quantifiers can model their temporal quantifiers in a reasonable way. From Mallya et al.'s approach, let $p$ be a proposition representing a ticket as an offer, so the proposition $[d_1, d_2]p$ denotes that the ticket will be an offer in the interval beginning at $d_1$ and ending at $d_2$. In our approach, $WCC(\mathit{TrCom}, \mathit{Cus}, \top, EF^{[1..24]}\ p))$ means that the travel company weakly commits to a customer to eventually make the ticket as an offer, which is only valid for an entire day (i.e., 24 hours). However, our quantified time intervals are not abstracted as propositions, as done in [15].

In the literature of agent communication, parallel with modeling commitments as temporal modalities, there are executable action languages [4,5], such as event calculus and causal logic C+, which model commitments as fluents. A fluent is a property, which has different values at different time points or can hold within time intervals. The current approaches use Boolean fluents, which have two possible values: true (hence commitments hold) and false (hence commitments do not hold). The operational semantics of commitment actions is defined by a set of axioms. In the event calculus formalism, this operational semantics is as follows: action occurrences are defined by the use of *happens* predicates, the effects of actions are defined by the use of *initiates* and *terminates* predicates and the fluents values are defined by the use of *initially, holdsAt* and *holdsFor* predicates. Although these executable action languages are very easily and efficiently implemented for executable system specifications, the underlying time model is linear (unlike our time branching model) and there is no formal semantics for commitments. Chesani et al. [4] extended the current event calculus formalism with data, variables, and metric time to deal with temporal aspects (e.g., deadlines). Like our approach, the authors argued that metric time is missing in temporal logics (e.g., LTL, CTL and CTL$^*$). From [4], consider the following axiom:

$$create(promise(Ag_1, Ag_2, deliverGoods), C(Ag_1, Ag_2, property(e(T_1, T_2), deliverGoods)), T) \leftarrow T_1 \ is \ \ T+1, T_2 \ is \ T+3.$$

Now, suppose we observed the following event: $promise(Mer, Cus, deliverGoods)$ at time 20. Since the signature of this event copes with the description of $create(\ldots)$, then $Mer$ becomes committed to deliver the requested goods between time 21 and time 23: $C(Mer, Cus, property(e(21, 23), deliverGoods))$. The Chesani et al.'s axiom can be defined using our logic as follows: $EF^{=20}promise(Mer, Cus, deliverGoods) \wedge SCC(Mer, Cus, \top, EF^{[21..23]}deliverGoods)$. Our approach can also extend the *content language* expressions in FIPA-ACL with interval operators to express assortment sets of temporal requirements, as done in [18].

## 4 Conclusion

We have shown how to extend the qualitative conditional commitment logic CTL$^{cc}$ to the quantitative logic called RTCTL$^{cc}$. The new logic is suitable for time-bounded reasoning about real-time MASs computing where the interaction among agents is modeled by conditional commitments and their fulfillment actions. We have also pointed out how quantitative properties expressed in the extended version of event calculus can be rigorously expressed in RTCTL$^{cc}$. As future work, we plan to develop a transformation algorithm to automatically transform the problem of model checking RTCTL$^{cc}$ into the problem of model checking RTCTL [13], so that the use of NuSMV is feasible. Given that, we plan to develop symbolic algorithms for bounded operators and implement them on top of our symbolic model checker MCMAS+ [6] to compare between direct and indirect verification techniques. We also plan to consider arbitrary durations in our model's transitions to have different levels of temporal deadlines and to reduce extra verification work resulting from the use of unit measure steps.

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