Real-Time Conditional Commitment Logic and Duration Communication Interpreted Systems

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Abstract. In this paper, we develop a real-time conditional and unconditional commitment logic (RTCTLC), which is interpreted over the Duration Communication Interpreted System (DCIS). The DCIS is the communication interpreted system with arbitrary integer durations on transitions. The transitions with durations allow us to model different levels of temporal deadlines and to reduce extra verification work resulting from the use of unit measure steps. The whole framework allows us to formally model the behaviour of agents using (conditional, unconditional, and group) commitments and real-time constraints in order to permit reasoning about qualitative and quantitative requirements.
Keywords: Real-time Conditional Commitment Logic, Duration Communication Interpreted System.

1 Introduction

Following Gerhard Weiss we define *multi-agent systems* (MASs) as "*systems in which several interacting, autonomous agents pursue some set of goals or perform some set of tasks*" [8]. Thus, the key property of MASs is the ability of agents to interact (communicate, negotiate, coordinate) with one another as well as their environments. Moreover, agents have the capabilities of reactivity (i.e., responding to external changes within your own environment), pro-activity (i.e., controlling your own behaviour in the furtherance of your own goals) and social ability (capability of interacting with other agents), and thereby they are intelligent entities.

The formalism of *interpreted systems* (IS) [5] provides a useful framework to model MASs and to verify various classes of temporal and epistemic properties only. The formalism of *communication interpreted systems* (CIS) [3] is an extension of ISs, which makes possible reasoning not only about temporal and epistemic agents' properties but also about their social abilities. In the paper we propose a new formalism of *duration communication interpreted systems* (DCIS), which compared to plain ISs and CISs has two properties that provide increased expressive power:

- Long steps: DCISs allow transitions to take a long time, e.g. 1000 time units. Such transitions would be obviously encoded in IS's by inserting 999 intermediate states. This, however, greatly increases the global state space of a given MAS and requires quite costly extra verification work. Thus, from the model checking [7] point of view it is better to have algorithms that understand arbitrary durations.
- Instantaneous steps: DCISs allow transitions to have zero duration. This is very convenient in models where some steps are described indirectly, as a short succession of micro-steps. Transitions with zero-duration are also a convenient way of counting specific actions only.

In the literature of agent communication, the social commitment has two forms: unconditional and conditional [2]. The basic idea of unconditional commitment is that the debtor agent makes a contractual obligation and he directs it towards the creditor agent, to bring about a certain fact. For example, the seller unconditionally commits to the buyer to ship the requested goods. The main idea of conditional commitments is that the debtor agent can merely commit towards the creditor agent to bring about consequences when specific conditions are met. For example, the seller commits to the buyer to ship the requested goods if the buyer sends the agreed payment.

The main objective of this paper is to provide a new agent communication language, called RTCTLC, that extends the RTCTL^{CC} [6] language with group conditional and unconditional social commitments modalities and their fulfillment modalities, and semantics of which is based on the duration communication interpreted systems. This new semantics allow us to consider arbitrary durations in our model's transitions and thereby to have different levels of temporal deadlines for unconditional and conditional commitments and their fulfillments.

The rest of the paper is organised as follows. In Section 2 we present the DCIS formalism together with its Kripke model, and we illustrate it by means of the Escrow protocol [1]. In section 3 we define the syntax and semantics of RTCTLC and we illustrate it, among others, by means of the properties of the Escrow protocol [1]. We conclude and identify future research directions in Section 4.

2 Duration Communication Interpreted System

A multi-agent system (MAS) is a non-empty and finite set of agents ($\mathbb{A} = \{1, \ldots, n\}$) together with the environment Env (a special agent), in which the agents operate. The formalism of interpreted systems [5] provides a very popular framework to model MASs. In [3] this formalism has been extended with sets of shared and unshared variables to account for agent communication; we refer to this extension as the communication interpreted system (CIS). In this paper, we extend the CIS formalism to account for durations that occurs during the execution of MAS, and we refer to it as the *duration communication interpreted system* (DCIS).

Let $\mathcal{PV} = \bigcup_{\mathbf{c}\in\mathbb{A}} \mathcal{PV}_{\mathbf{c}} \cup \mathcal{PV}_{\mathrm{Env}}$ be a set of propositional variables such that $\mathcal{PV}_{\mathbf{c}_1} \cap \mathcal{PV}_{\mathbf{c}_2} = \emptyset$ for all $\mathbf{c}_1, \mathbf{c}_2 \in \mathbb{A} \cup \{\mathrm{Env}\}$. In DCIS, each agent $\mathbf{c} \in \mathbb{A}$ is characterized by:

- $L_{\mathbf{c}}$ - a non-empty and finite set of *local states*, which models the instantaneous configuration of the agent $\mathbf{c}$ in MAS.
- $Var_{\mathbf{c}}$ - a finite set of at most $n-1$ non-negative local *integer variables* that represent communication channels through which messages are sent and received, and to define the *social accessibility* relation.
- $Act_{\mathbf{c}}$ - a non-empty and finite set of possible *actions* such that the special *null* action $\epsilon_{\mathbf{c}}$ belongs to $Act_{\mathbf{c}}$; it is assumed that actions are "public".
- $D_{\mathbf{c}} : Act_{\mathbf{c}} \to \mathbb{N}$ - a *duration* function that assigns to every action a natural number, called the *duration* of the action.
- $P_{\mathbf{c}} : L_{\mathbf{c}} \to 2^{Act_{\mathbf{c}}}$ - a *protocol* function that assigns to every local state a set of actions that can be fired at that state.
- $t_{\mathbf{c}} : L_{\mathbf{c}} \times L_{\mathrm{Env}} \times Act \to L_{\mathbf{c}}$ - a (partial) local *evolution* function. Each element of $Act = \prod_{\mathbf{c}\in\mathbb{A}\cup\{\mathrm{Env}\}} Act_{\mathbf{c}}$, as usually, is called the *joint action*. We assume that if $\epsilon_{\mathbf{c}} \in P_{\mathbf{c}}(\ell_{\mathbf{c}})$, then $t_{\mathbf{c}}(\ell_{\mathbf{c}}, \ell_{\mathrm{Env}}, (a_1, \ldots, a_n, a_{\mathrm{Env}})) = \ell_{\mathbf{c}}$ for $a_{\mathbf{c}} = \epsilon_{\mathbf{c}}$.
- $V_{\mathbf{c}} : L_{\mathbf{c}} \to 2^{\mathcal{PV}_{\mathbf{c}}}$ - a *valuation function* which assigns to every local state a set of propositional variables that are assumed to be true at that state.

The environment Env plays a key role in MAS as a source of information that is not specific to any individual agent and it is characterized by:

- L_{Env} - a non-empty and finite set of local *states*.
- Act_{Env} - a non-empty and finite set of possible *actions*.
- $D_{\mathrm{Env}} : Act_{\mathrm{Env}} \to \mathbb{N}$ - a *duration* function.
- $P_{\mathrm{Env}} : L_{\mathrm{Env}} \to 2^{Act_{\mathrm{Env}}}$ - a *protocol* function.
- $t_{\mathrm{Env}} : L_{\mathrm{Env}} \times Act \to L_{\mathrm{Env}}$ - a (partial) *evolution* function.
- $V_{\mathrm{Env}} : L_{\mathrm{Env}} \to 2^{\mathcal{PV}_{\mathrm{Env}}}$ - a *valuation* function.

It is assumed that local states and actions for Env are "public".

A set of all *global states* is defined as $S = L_1 \times \ldots \times L_n \times L_{\mathrm{Env}}$ [5], and each element $s \in S$ represents some instantaneous configuration of the given MAS. Thus, given a set of agents $\mathbb{A}$, the environment Env, and a set of initial global states $\iota \subseteq S$, we call the tuple

$$\mathcal{D} = (\{L_{\mathbf{c}}, Act_{\mathbf{c}}, P_{\mathbf{c}}, D_{\mathbf{c}}, t_{\mathbf{c}}, V_{\mathbf{c}}\}_{\mathbf{c}\in\mathbb{A}\cup\{\mathrm{Env}\}}, \{Var_{\mathbf{c}}\}_{\mathbf{c}\in\mathbb{A}}, \iota)$$

the *duration communication interpreted system* (DCIS).

Let $s = (\ell_1, \ldots, \ell_n, \ell_{\mathrm{Env}})$ be a global state and $l_{\mathbf{c}}(s)$ denote the local state of $\mathbf{c} \in \mathbb{A} \cup \{\mathrm{Env}\}$ in s. A *global evolution function* $t : S \times Act \to S$ is defined as usually by $t(s, a) = s'$ iff $t_{\mathbf{c}}(l_{\mathbf{c}}(s), l_{\mathrm{Env}}(s), a) = l_{\mathbf{c}}(s')$ for all $\mathbf{c} \in \mathbb{A}$ and $t_{\mathrm{Env}}(l_{\mathrm{Env}}(s), a) = l_{\mathrm{Env}}(s')$. In brief we write the above as $s \xrightarrow{a} s'$. Furthermore, following [3], we denote the value of a variable $x \in Var_{\mathbf{c}}$ at local state $l_{\mathbf{c}}(s)$ by $l^x_{\mathbf{c}}(s)$, and we assume that if $l_{\mathbf{c}}(s) = l_{\mathbf{c}}(s')$, then $l^x_{\mathbf{c}}(s) = l^x_{\mathbf{c}}(s')$ for all $x \in Var_{\mathbf{c}}$. Next, for each pair $(\mathbf{c}_1, \mathbf{c}_2)$ of agents in $\mathbb{A}$, $\sim_{\mathbf{c}_1\to\mathbf{c}_2} \subseteq S \times S$ is a serial *social accessibility* relation defined by $s \sim_{\mathbf{c}_1\to\mathbf{c}_2} s'$ iff the following conditions are true:

- $l_{\mathbf{c}_1}(s) = l_{\mathbf{c}_1}(s')$, and
- $s \xrightarrow{a} s'$ for some $a \in Act$, and
- $Var_{\mathbf{c}_1} \cap Var_{\mathbf{c}_2} \neq \emptyset$ and $\forall x \in Var_{\mathbf{c}_1} \cap Var_{\mathbf{c}_2}$ we have $l^x_{\mathbf{c}_1}(s) = l^x_{\mathbf{c}_2}(s')$, and
- $\forall y \in Var_{\mathbf{c}_2} - Var_{\mathbf{c}_1}$ we have $l^y_{\mathbf{c}_2}(s) = l^y_{\mathbf{c}_2}(s')$.

The intuition behind the social accessibility relation $\sim_{\mathbf{c}_1 \to \mathbf{c}_2}$ from a global state s to another global state s' is the following. Since $\mathbf{c}_1$ initiates the communication and it does not learn any new information, the states s and s' are indistinguishable for $\mathbf{c}_1$ ($l_{\mathbf{c}_1}(s) = l_{\mathbf{c}_1}(s')$). The global state s' is reachable from state s via some joint action. There is a communication channel between $\mathbf{c}_1$ and $\mathbf{c}_2$ ($Var_{\mathbf{c}_1} \cap Var_{\mathbf{c}_2} \neq \emptyset$). The channel is filled in by $\mathbf{c}_1$ in state s, and in state s' $\mathbf{c}_2$ receives the information, which makes the value of the shared variable the same for $\mathbf{c}_1$ and $\mathbf{c}_2$ ($l^x_{\mathbf{c}_1}(s) = l^x_{\mathbf{c}_2}(s')$). The states s and s' are indistinguishable for $\mathbf{c}_2$ with regard to the variables that have not been communicated by $\mathbf{c}_1$, i.e., unshared variables ($(\forall y \in Var_{\mathbf{c}_2} - Var_{\mathbf{c}_1})\ l^y_{\mathbf{c}_2}(s) = l^y_{\mathbf{c}_2}(s')$).

2.1 Model

For a given duration communication interpreted system $\mathcal{D}$ we define a *model* as a tuple

$$M = (Act, S, \iota, T, D, V, \sim_{\mathbf{c}_1 \to \mathbf{c}_2}), \text{ where}$$

- Act is the set of joint actions.
- S is a set of global states that is defined as above, and $\iota \subseteq S$.
- $T \subseteq S \times Act \times S$ is a transition relation on S defined by: $(s, a, s') \in T$ iff $s \xrightarrow{a} s'$. We assume that the relation T is total, i.e., for any $s \in S$ there exists $s' \in S$ and an action $a \in Act \setminus \{\overline{\epsilon}\}$ such that $s \xrightarrow{a} s'$ and $\overline{\epsilon} = (\epsilon_1, \ldots, \epsilon_n, \epsilon_{\mathrm{Env}})$.
- Let the maximum value of a set of elements $\mathbb{D} = \{D_1(a_1), \ldots, D_n(a_n), D_{\mathrm{Env}}(a_{\mathrm{Env}})\}$ be denoted by $max(\mathbb{D})$. The *global duration* function $D : Act \to \mathbb{N}$ is defined as $D((a_1, \ldots, a_n, a_{\mathrm{Env}})) = max(\mathbb{D})$.
- $V : S \to 2^{\mathcal{PV}}$ is the *global valuation* function defined as $V(s) = \bigcup_{\mathbf{c} \in \mathbb{A} \cup \{\mathrm{Env}\}} V_{\mathbf{c}}(l_{\mathbf{c}}(s))$.
- $\sim_{\mathbf{c}_1 \to \mathbf{c}_2} \subseteq S \times S$ is the social accessibility relation for $\mathbf{c}_1 \in \mathbb{A}$ and $\mathbf{c}_2 \in \mathbb{A}$.

Observe that each transition in our quantitative temporal model M may take an arbitrary time unit for execution from one state to another state. For example, during a transition $s \xrightarrow{a} s'$ with $D(a) = 8$, the system moves from "s at some time t" to "s' at $t + 8$": between t and $t + 8$, there is no state (or time) where the system is in.

The underlying real-time model is discrete and has a tree-like structure. The model M can be unfolded into a set of execution *paths* in which each *path* $\pi = s_0 \xrightarrow{a_1} s_1 \xrightarrow{a_2} s_2 \xrightarrow{a_3} \ldots$ is an infinite sequence of linked transitions. For such a path and for $m \in \mathbb{N}$, we denote by $\pi(m)$ the m-th state s_m. Finally, for $j \leq m \in \mathbb{N}$, we denote by $\pi[j..m]$ the finite sequence $s_j \xrightarrow{a_{j+1}} s_{j+1} \xrightarrow{a_{j+2}} \ldots s_m$ with $m - j$ transitions and $m - j + 1$ states. The (cumulative) duration $\mathrm{D}(\pi[j..m])$ of the finite sequence $\pi[j..m]$ is $D(a_{j+1}) + \ldots + D(a_m)$ (hence 0 when $j = m$). We write $\Pi(s)$ for the set of all the paths that start at $s \in S$, and $\Pi = \bigcup_{s^0 \in \iota} \Pi(s^0)$ for the set of all the paths starting at initial states.

2.2 Escrow Protocol

The escrow protocol [1] is a three-party protocol involving a buyer, a seller and a trusted third-party escrow. The Escrow protocol works as follows:

1. Either the Buyer or the Seller begins a transaction. Buyer and Seller agree to the terms of the transaction via `Escrow.com`.
2. The Buyer deposits the payment to the secure Escrow account.
3. `Escrow.com` verifies the payment and notifies the Seller that funds have been secured in Escrow.
4. The Seller ships the goods to the Buyer - Upon payment verification, the Seller is authorised to send the goods and submit tracking information. `Escrow.com` verifies that the Buyer receives the goods.
5. The Buyer has a set number of days to inspect the goods and the option to accept or reject it. If the Buyer is satisfied, he authorises the Escrow to pay the Seller. `Escrow.com` then pays the Seller. However, if the Buyer is not satisfied, in addition to notifying the escrow, he returns the goods to the Seller. When the Seller notifies the escrow about the goods being received back, the Escrow refunds the deposit to the Buyer with a set number of days.

Modelling the Escrow protocol. In line with the spirit of the interpreted systems formalism, it is convenient to see the Buyer ($\mathcal{B}$), the Seller ($\mathcal{S}$) and the Escrow ($\mathcal{E}$) as agents, and the communication channel as the environment Env. Thus $\mathbb{A} = \{\mathcal{B}, \mathcal{S}, \mathcal{E}\}$ is the set of agents of the Escrow protocol. Each agent of the Escrow protocol can be modelled by considering its finite set of local states, finite set of local non-negative integer variables, finite set of local actions, the local duration function, the local protocol function, the local evolution function, and the local valuation function, i.e., the associated duration communication interpreted system is the following:

$$\mathcal{D} = (\{L_{\mathbf{c}}, Act_{\mathbf{c}}, P_{\mathbf{c}}, D_{\mathbf{c}}, t_{\mathbf{c}}, V_{\mathbf{c}}\}_{\mathbf{c}\in\mathbb{A}\cup\{\mathrm{Env}\}}, \{Var_{\mathbf{c}}\}_{\mathbf{c}\in\mathbb{A}}, \iota), \text{ where}$$

– $L_{\mathcal{B}} = \{b_0, b_1, b_2, b_3, b_4, b_5, b_6\}$. The meaning of local states is the following:
- b_0 - initiate the transaction (contract) by submitting the payment to Escrow.
- b_1 - wait for the goods.
- b_2 - inspect the goods and make a decision on their acceptance or rejection.
- b_3 - authorize the Escrow to pay the Seller. The contract is fulfilled successfully.
- b_4 - return the goods to the Seller.
- b_5 - wait for the refund from the Escrow.
- b_6 - the contract is violated by the Buyer.

$L_{\mathcal{S}} = \{m_0, m_1, m_2, m_3, m_4, m_5\}$. The meaning of local states is the following:
- m_0 - wait for the payment to Escrow from the Buyer.
- m_1 - shipping the goods to the Buyer.
- m_2 - wait for the Buyer's decision.
- m_3 - wait for the payment from Escrow.

  - m_4 - wait for the goods from the Buyer and notify the Escrow about the goods being received.
  - m_5 - the contract is violated by the Buyer.

  $L_{\mathcal{E}} = \{e_0, e_1, e_2, e_3, e_4, e_5, e_6, e_7\}$. The meaning of local states is the following:
  - e_0 - wait for the Buyer to make the payment.
  - e_1 - notify the Seller that the payment was made.
  - e_2 - wait for the Seller to ship the goods and Buyer to make a decision.
  - e_3 - pay the Seller.
  - e_4 - wait for the Buyer to return goods.
  - e_5 - the contract is fulfilled successfully.
  - e_6 - refund the deposit to the Buyer.
  - e_7 - the contract is violated by the Buyer.

  For simplicity, we shall take the local states of the environment to be just a singleton: $L_{\mathrm{Env}} = \{\cdot\}$. This is to simplify the presentation. Thus the global set of states $S = L_{\mathcal{B}} \times L_{\mathcal{S}} \times L_{\mathcal{E}} \times L_{\mathrm{Env}}$.
- the sets of natural (non-negative) variables available to the agents are: $Var_{\mathcal{B}} = \{x_1, x_2\}$, $Var_{\mathcal{S}} = \{x_1, x_3\}$ and $Var_{\mathcal{E}} = \{x_2, x_3\}$. The variable x_1 represents the communication channel between $\mathcal{B}$ and $\mathcal{S}$. The variable x_2 represents the communication channel between $\mathcal{B}$ and $\mathcal{E}$. The variable x_3 represents the communication channel between $\mathcal{S}$ and $\mathcal{E}$.
- the sets of local actions are:
  - $Act_{\mathcal{B}} = \{deposit, returnGoods, goodsOk, goodsNotOk, end_B, \epsilon_B\}$, where ϵ_B stands for the null action.
  - $Act_{\mathcal{S}} = \{sendGoods, release, end_S, \epsilon_S\}$, where ϵ_S stands for the null action.
  - $Act_{\mathcal{E}} = \{notify, refund, pay, end_{\mathcal{E}}, \epsilon_{\mathcal{E}}\}$, where $\epsilon_{\mathcal{E}}$ stands for the null action.
  - $Act_{\mathrm{Env}} = \{\leftrightarrows\}$, where $\leftrightarrows$ represents the action in which the channel transmits any message successfully in both directions. For simplicity, we assume that the channel always works properly.

  Thus, $Act = Act_{\mathcal{B}} \times Act_{\mathcal{S}} \times Act_{\mathcal{E}} \times Act_{\mathrm{Env}}$.
- the local protocols of the agents and the environment are:
  - $P_{\mathcal{B}}(b_0) = \{deposit\}$; $P_{\mathcal{B}}(b_1) = \{\epsilon_B\}$; $P_{\mathcal{B}}(b_2) = \{goodsOk, goodsNotOk\}$; $P_{\mathcal{B}}(b_3) = \{end_B, \epsilon_B\}$; $P_{\mathcal{B}}(b_4) = \{returnGoods\}$; $P_{\mathcal{B}}(b_5) = \{\epsilon_B\}$; $P_{\mathcal{B}}(b_6) = \{end_B\}$.
  - $P_{\mathcal{S}}(m_0) = \{\epsilon_S\}$; $P_{\mathcal{S}}(m_1) = \{sendGoods\}$; $P_{\mathcal{S}}(m_2) = \{\epsilon_S\}$; $P_{\mathcal{S}}(m_3) = \{end_S\}$; $P_{\mathcal{S}}(m_4) = \{release\}$; $P_{\mathcal{S}}(m_5) = \{end_S\}$;
  - $P_{\mathcal{E}}(e_0) = \{\epsilon_{\mathcal{E}}\}$; $P_{\mathcal{E}}(e_1) = \{notify\}$; $P_{\mathcal{E}}(e_2) = \{\epsilon_{\mathcal{E}}\}$; $P_{\mathcal{E}}(e_3) = \{pay\}$; $P_{\mathcal{E}}(e_4) = \{\epsilon_{\mathcal{E}}\}$; $P_{\mathcal{E}}(e_5) = \{end_{\mathcal{E}}\}$; $P_{\mathcal{E}}(e_6) = \{refund\}$; $P_{\mathcal{E}}(e_7) = \{end_{\mathcal{E}}\}$;
  - $P_{\mathrm{Env}}(\cdot) = \{\leftrightarrows\}$;
- the local durations of the agents and the environment are:
  - $D_{\mathcal{B}}(goodsOk) = D_{\mathcal{B}}(goodsNotOk) = 14$,
    $D_{\mathcal{B}}(deposit) = D_{\mathcal{B}}(returnGoods) = D_{\mathcal{B}}(end_B) = 0$. This means that the Buyer has 14 days to make a decision.
  - $D_{\mathcal{S}}(sendGoods) = 3$, $D_{\mathcal{S}}(release) = 2$, $D_{\mathcal{S}}(end_S) = 0$. This means that the Seller has 2 days to release the deposit and 3 days to ship goods.
  - $D_{\mathcal{E}}(notify) = D_{\mathcal{E}}(refund) = D_{\mathcal{E}}(pay) = D_{\mathcal{E}}(end_{\mathcal{E}}) = 0$.

- Let $\overline{\epsilon}$ be the joint null action (i.e., the action composed of the null actions only), *state* denote a local state of an agent, $a \in Act$, $act_{\mathcal{B}}(a)$ denote an action of $\mathcal{B}$, $act_{\mathcal{S}}(a)$ denote an action of $\mathcal{S}$, $act_{\mathcal{E}}(a)$ denote an action of $\mathcal{E}$, and $act_{\mathrm{Env}}(a)$ denote an action of Env. We assume the following local evolution functions.

  The Buyer:

  - $t_{\mathcal{B}}(state, \cdot, a) = state$ if $a \neq \overline{\epsilon}$ and $act_{\mathcal{B}}(a) = \epsilon_{\mathcal{B}}$.
  - $t_{\mathcal{B}}(b_0, \cdot, a) = b_1$ if $act_{\mathcal{B}}(a) = deposit$.
  - $t_{\mathcal{B}}(b_1, \cdot, a) = b_2$ if $act_{\mathcal{S}}(a) = sendGoods$.
  - $t_{\mathcal{B}}(b_2, \cdot, a) = b_3$ if $act_{\mathcal{B}}(a) = goodsOk$.
  - $t_{\mathcal{B}}(b_2, \cdot, a) = b_4$ if $act_{\mathcal{B}}(a) = goodsNotOk$.
  - $t_{\mathcal{B}}(b_4, \cdot, a) = b_5$ if $act_{\mathcal{B}}(a) = returnGoods$.
  - $t_{\mathcal{B}}(b_5, \cdot, a) = b_6$ if $act_{\mathcal{E}}(a) = refund$.
  - $t_{\mathcal{B}}(b_6, \cdot, a) = b_0$ if $act_{\mathcal{B}}(a) = end_{\mathcal{B}}$ and $act_{\mathcal{E}}(a) = end_{\mathcal{E}}$.
  - $t_{\mathcal{B}}(b_3, \cdot, a) = b_0$ if $act_{\mathcal{B}}(a) = end_{\mathcal{B}}$ and $act_{\mathcal{E}}(a) = end_{\mathcal{E}}$.

  The Seller:

  - $t_{\mathcal{S}}(state, \cdot, a) = state$ if $a \neq \overline{\epsilon}$ and $act_{\mathcal{S}}(a) = \epsilon_{\mathcal{S}}$.
  - $t_{\mathcal{B}}(m_0, \cdot, a) = m_1$ if $act_{\mathcal{E}}(a) = notify$.
  - $t_{\mathcal{B}}(m_1, \cdot, a) = m_2$ if $act_{\mathcal{S}}(a) = sendGoods$.
  - $t_{\mathcal{B}}(m_2, \cdot, a) = m_3$ if $act_{\mathcal{E}}(a) = pay$.
  - $t_{\mathcal{B}}(m_2, \cdot, a) = m_4$ if $act_{\mathcal{B}}(a) = returnGoods$.
  - $t_{\mathcal{B}}(m_4, \cdot, a) = m_5$ if $act_{\mathcal{S}}(a) = release$.
  - $t_{\mathcal{B}}(m_5, \cdot, a) = m_0$ if $act_{\mathcal{S}}(a) = end_S$ and $act_{\mathcal{E}}(a) = end_{\mathcal{E}}$.
  - $t_{\mathcal{B}}(m_3, \cdot, a) = m_0$ if $act_{\mathcal{S}}(a) = end_S$ and $act_{\mathcal{E}}(a) = end_{\mathcal{E}}$ and $act_{\mathcal{B}}(a) = end_B$.

  The Escrow:

  - $t_{\mathcal{E}}(state, \cdot, a) = state$ if $a \neq \overline{\epsilon}$ and $act_{\mathcal{E}}(a) = \epsilon_{\mathcal{E}}$.
  - $t_{\mathcal{E}}(e_0, \cdot, a) = e_1$ if $act_{\mathcal{B}}(a) = deposit$.
  - $t_{\mathcal{E}}(e_1, \cdot, a) = e_2$ if $act_{\mathcal{E}}(a) = notify$.
  - $t_{\mathcal{E}}(e_2, \cdot, a) = e_3$ if $act_{\mathcal{B}}(a) = goodsOk$.
  - $t_{\mathcal{E}}(e_2, \cdot, a) = e_4$ if $act_{\mathcal{B}}(a) = goodsNotOk$.
  - $t_{\mathcal{E}}(e_3, \cdot, a) = e_5$ if $act_{\mathcal{E}}(a) = pay$.
  - $t_{\mathcal{E}}(e_4, \cdot, a) = e_6$ if $act_{\mathcal{S}}(a) = release$.
  - $t_{\mathcal{E}}(e_6, \cdot, a) = e_7$ if $act_{\mathcal{E}}(a) = refund$.
  - $t_{\mathcal{E}}(e_7, \cdot, a) = e_0$ if $act_{\mathcal{B}}(a) = end_B$ and $act_{\mathcal{E}}(a) = end_{\mathcal{E}}$.
  - $t_{\mathcal{E}}(e_5, \cdot, a) = e_0$ if $act_{\mathcal{B}}(a) = end_B$ and $act_{\mathcal{E}}(a) = end_{\mathcal{E}}$.

The set of possible global states S for the Escrow protocol is defined as the product $L_{\mathcal{B}} \times L_{\mathcal{S}} \times L_{\mathcal{E}} \times L_{\mathrm{Env}}$. Moreover, we consider the following set of initial states $\iota = \{(b_0, m_0, e_0, \cdot)\}$.

In the Kripke model of the Escrow protocol, we assume the following set of proposition variables:

$\mathcal{PV} = \{deposit, delivered, goodsOk, goodsNotOk, returnGoods, refund\}$

with the following interpretation:
$(M, s) \models \mathit{deposit}$ if $l_{\mathcal{B}}(s) = b_1$
$(M, s) \models \mathit{delivered}$ if $l_{\mathcal{B}}(s) = b_2$ and $l_{\mathcal{S}} = m_2$ and $l_{\mathcal{E}} = e_2$
$(M, s) \models \mathit{goodsNotOk}$ if $l_{\mathcal{B}}(s) = b_4$
$(M, s) \models \mathit{goodsOk}$ if $l_{\mathcal{B}}(s) = b_3$ and $l_{\mathcal{S}} = m_2$
$(M, s) \models \mathit{returnGoods}$ if $l_{\mathcal{B}}(s) = b_5$ and $l_{\mathcal{S}} = m_4$
$(M, s) \models \mathit{refund}$ if $l_{\mathcal{B}}(s) = b_6$

3 The Real-Time Conditional Commitment Logic

The Real-Time Conditional Commitment Logic (RTCTLC) is a combination of RTCTL [4], a branching temporal logic with timing constraints, with the commitment modality [3], the group commitment modality [9], the conditional commitment modality [6], the conditional group commitment modality, the fulfillment of the commitment modality [3], the fulfillment of the group commitment modality, the fulfillment of the conditional commitment modality [6] and the fulfillment of the conditional group commitment modality.

3.1 Syntax of RTCTLC

Let $p \in \mathcal{PV}$ be a propositional variable, $\mathbf{c}, \mathbf{c}_1, \mathbf{c}_2 \in \mathbb{A}$, $\Gamma \subseteq \mathbb{A}$, and I is an interval in $\mathbb{N}$ of the form: $[a, b)$ and $[a, \infty)$, for $a, b \in \mathbb{N}$ and $a \neq b$. We define RTCTLC formulae inductively via a Backus Naur form as follows:

$$\begin{aligned}
\varphi ::= & \mathbf{true} \mid \mathbf{false} \mid p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \mathrm{EX}\varphi \mid \mathrm{E}(\varphi \mathrm{U}_I \varphi) \mid \mathrm{A}(\varphi \mathrm{U}_I \varphi) \mid CC \mid Fu \\
CC ::= & \mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}(\varphi) \mid \mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\varphi, \varphi) \mid \mathrm{C}_{\mathbf{c}_1 \to \Gamma}(\varphi) \mid \mathrm{CC}_{\mathbf{c} \to \Gamma}(\varphi, \varphi) \mid \\
Fu ::= & \mathrm{Fu}(\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}(\varphi)) \mid \mathrm{Fu}(\mathrm{C}_{\mathbf{c} \to \Gamma}(\varphi)) \mid \mathrm{Fu}(\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\varphi, \varphi)) \mid \mathrm{Fu}(\mathrm{CC}_{\mathbf{c} \to \Gamma}(\varphi, \varphi))
\end{aligned}$$

where

- $\neg$ and $\wedge$ are the standard Boolean connectives for negation and conjunction, respectively. The other propositional connectives are defined as abbreviations in the standard way: $\vee$ for disjunction, $\Rightarrow$ for implication, and $\Leftrightarrow$ for logical equivalence.
- EX, EU$_I$and AU$_I$ are modalities of RTCTL standing for "existential neXt state", "existential bounded Until", and "universal bounded Until", respectively. Other basic modalities of RTCTL are also defined as abbreviations: $\mathrm{AF}_I\varphi := \mathrm{A}(\mathbf{true}\mathrm{U}_I\varphi)$ (*universal bounded Future state*), $\mathrm{EF}_I\varphi := \mathrm{E}(\mathbf{true}\mathrm{U}_I\varphi)$ (*existential bounded Future state*), $\mathrm{AG}_I\varphi := \neg\mathrm{EF}_I\neg\varphi$ (*universal bounded Globally*), $\mathrm{EG}_I\varphi := \neg\mathrm{AF}_I\neg\varphi$ (*existential bounded Globally*), and $\mathrm{AX}\varphi := \neg\mathrm{EX}\neg\varphi$ (*universal neXt state*).
- $\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}$, $\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}$, $\mathrm{C}_{\mathbf{c} \to \Gamma}$, and $\mathrm{CC}_{\mathbf{c} \to \Gamma}$ stand for *commitment*, *conditional commitment*, *group commitment* and *group conditional commitment*. The formula $\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}(\varphi)$ is read as "agent $\mathbf{c}_1$ commits towards agent $\mathbf{c}_2$ that φ". The formula $\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi)$ is read as "agent $\mathbf{c}_1$ commits towards agent $\mathbf{c}_2$ to consequently

satisfy φ once the antecedent ψ holds". The formula $\mathrm{C}_{\mathbf{c} \to \Gamma}(\varphi)$ is read as "agent $\mathbf{c}_1$ commits towards agents in Γ that φ". The formula $\mathrm{CC}_{\mathbf{c} \to \Gamma}(\psi, \varphi)$ is read as "agent $\mathbf{c}_1$ commits towards agents in Γ to consequently satisfy φ once the antecedent ψ holds".

- $\mathrm{Fu}(\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2})$, $\mathrm{Fu}(\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2})$, $\mathrm{Fu}(\mathrm{C}_{\mathbf{c} \to \Gamma})$, and $\mathrm{Fu}(\mathrm{CC}_{\mathbf{c} \to \Gamma})$ stand for *fulfillments* of *commitment*, *conditional commitment*, *group commitment*, and *group conditional commitment*, respectively. $Fu(\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}(\varphi))$ is read as "the commitment $\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}(\varphi)$ is fulfilled". $Fu(\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi))$ is read as "the conditional commitment $\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi)$ is fulfilled". $Fu(\mathrm{C}_{\mathbf{c}_1 \to \Gamma}(\varphi))$ is read as "the group commitment $\mathrm{C}_{\mathbf{c}_1 \to \Gamma}(\varphi)$ is fulfilled". $Fu(\mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi))$ is read as "the group conditional commitment $\mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi)$ is fulfilled".

3.2 Semanitics of RTCTLC

RTCTLC formulae are interpreted over models generated by duration communication interpreted systems. Let $M = (Act, S, \iota, T, D, V, \sim_{\mathbf{c}_1 \to \mathbf{c}_2})$ be such a model, $s \in S$, φ a RTCTLC formula, and $s \sim_{\mathbf{c}_1 \to \Gamma} s' \overset{def}{=} (\forall \mathbf{c}_2 \in \Gamma)(s \sim_{\mathbf{c}_1 \to \mathbf{c}_2} s')$. The definition of whether $M, s \models \varphi$ holds is recursive on the structure of φ. Namley, the relation $M, s \models \varphi$ is defined by structural induction on φ:

$$\begin{aligned}
M, s &\models \mathbf{true},\ M, s \not\models \mathbf{false}, \\
M, s \models p &\text{ iff } p \in V(s), \\
M, s \models \neg\varphi &\text{ iff } M, s \not\models \varphi, \\
M, s \models \varphi \wedge \psi &\text{ iff } M, s \models \varphi \text{ and } M, s \models \psi, \\
M, s \models \mathrm{EX}\varphi &\text{ iff } (\exists \pi \in \Pi(s)) M, \pi(1) \models \varphi, \\
M, s \models \mathrm{E}(\varphi \mathrm{U}_I \psi) &\text{ iff } (\exists \pi \in \Pi(s))(\exists m \geq 0)(D\pi[0..m] \in I \text{ and} \\
&\phantom{\text{ iff }} M, \pi(m) \models \psi \text{ and } (\forall j < m) M, \pi(j) \models \varphi), \\
M, s \models \mathrm{A}(\varphi \mathrm{U}_I \psi) &\text{ iff } (\forall \pi \in \Pi(s))(\exists m \geq 0)(D\pi[0..m] \in I \text{ and} \\
&\phantom{\text{ iff }} M, \pi(m) \models \psi \text{ and } (\forall j < m) M, \pi(j) \models \varphi), \\
M, s \models \mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}\varphi &\text{ iff } (\forall s' \in S)(s \sim_{\mathbf{c}_1 \to \mathbf{c}_2} s' \text{ implies } M, s' \models \varphi), \\
M, s \models \mathrm{C}_{\mathbf{c}_1 \to \Gamma}\varphi &\text{ iff } (\forall s' \in S)(s \sim_{\mathbf{c}_1 \to \Gamma} s' \text{ implies } M, s' \models \varphi), \\
M, s \models \mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi) &\text{ iff } (\forall s' \in S)(s \sim_{\mathbf{c}_1 \to \mathbf{c}_2} s' \text{ and } M, s' \models \psi \\
&\phantom{\text{ iff }} \text{implies } M, s' \models \varphi), \\
M, s \models \mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi) &\text{ iff } (\forall s' \in S)(s \sim_{\mathbf{c}_1 \to \Gamma} s' \text{ and } M, s' \models \psi \\
&\phantom{\text{ iff }} \text{implies } M, s' \models \varphi), \\
M, s \models \mathrm{Fu}(\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}\varphi) &\text{ iff } (\exists s' \in S)(s' \sim_{\mathbf{c}_1 \to \mathbf{c}_2} s \text{ and } M, s' \models \mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}\varphi \text{ and} \\
&\phantom{\text{ iff }} M, s \models \varphi \wedge \neg\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}\varphi), \\
M, s \models \mathrm{Fu}(\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi)) &\text{ iff } (\exists s' \in S)(s' \sim_{\mathbf{c}_1 \to \mathbf{c}_2} s \text{ and } M, s' \models \mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi) \\
&\phantom{\text{ iff }} \text{and } M, s \models \varphi \wedge \neg\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi)), \\
M, s \models \mathrm{Fu}(\mathrm{C}_{\mathbf{c}_1 \to \Gamma}\varphi) &\text{ iff } (\exists s' \in S)(s' \sim_{\mathbf{c}_1 \to \Gamma} s \text{ and } M, s' \models \mathrm{C}_{\mathbf{c}_1 \to \Gamma}\varphi \\
&\phantom{\text{ iff }} \text{and } M, s \models \varphi \wedge \neg\mathrm{C}_{\mathbf{c}_1 \to \Gamma}\varphi), \\
M, s \models \mathrm{Fu}(\mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi)) &\text{ iff } (\exists s' \in S)(s' \sim_{\mathbf{c}_1 \to \Gamma} s \text{ and } M, s' \models \mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi) \\
&\phantom{\text{ iff }} \text{and } M, s \models \varphi \wedge \neg\mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi)).
\end{aligned}$$

- A RTCTLC formula φ is *universally valid* in M, denoted by $M \models \varphi$, iff for each $s \in \iota$, $M, s \models \varphi$, i.e., φ holds at every initial state of M.
- A RTCTLC formula φ is *existentially valid* in M, denoted by $M \models^{\exists} \varphi$, iff for some $s \in \iota$, $M, s \models \varphi$, i.e., φ holds at some initial state of M.
- Determining whether a RTCTLC formula φ is existentially (resp. universally) valid in the model M is called an *existential* (resp. *universal*) model checking problem. In other words, the *universal model checking problem* asks whether $M \models \varphi$, and the *existential model checking problem* asks whether $M \models^{\exists} \varphi$.

For the propositions, Boolean connectives and temporal modalities, the relation $\models$ is defined in the standard manner. The state formulae $\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}\varphi$ and $\mathrm{C}_{\mathbf{c}_1 \to \Gamma}\varphi$ are satisfied in the model M at state s iff the formula φ holds in every accessible state obtained by the accessibility relations $\sim_{\mathbf{c}_1 \to \mathbf{c}_2}$ and $\sim_{\mathbf{c}_1 \to \Gamma}$, respectively. The state formulae $\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi)$ and $\mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi)$ are satisfied in the model M at state s iff the formula φ holds in every state that satisfies formula ψ and which is accessible by the accessibility relations $\sim_{\mathbf{c}_1 \to \mathbf{c}_2}$ and $\sim_{\mathbf{c}_1 \to \Gamma}$, respectively. Observe that unconditional commitments are a special case of conditional commitments when the antecedents are always true.

The state formulae $Fu(\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}\varphi)$ and $Fu(\mathrm{C}_{\mathbf{c}_1 \to \Gamma}\varphi)$ are satisfied in the model M at state s iff s satisfies φ and the negation of the commitments $\mathrm{C}_{\mathbf{c}_1 \to \mathbf{c}_2}\varphi$ and $\mathrm{C}_{\mathbf{c}_1 \to \Gamma}\varphi$, respectively, and there exists a state s' satisfying the commitment from which the state s is reachable via the accessability relations $\sim_{\mathbf{c}_1 \to \mathbf{c}_2}$ and $\sim_{\mathbf{c}_1 \to \Gamma}$, respectively. The state formulae $Fu(\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi))$ and $Fu(\mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi))$ are satisfied in the model M at state s iff s satisfies φ and the negation of the commitments $\mathrm{CC}_{\mathbf{c}_1 \to \mathbf{c}_2}(\psi, \varphi)$ and $\mathrm{CC}_{\mathbf{c}_1 \to \Gamma}(\psi, \varphi)$, respectively, and there exists a state s' satisfying the commitment from which the state s is reachable via the accessability relations $\sim_{\mathbf{c}_1 \to \mathbf{c}_2}$ and $\sim_{\mathbf{c}_1 \to \Gamma}$, respectively. The idea behind this semantics is to say that a commitment is fulfilled when we reach an accessible state from the commitment state in which the formula φ holds and the commitment becomes no longer active.

We conclude this section by illustrating how the basic RTCTLC modalities could be used to express important correctness properties of commitment protocols that must place an explicit bound on the time between events. First, observe that $\mathrm{AF}_I p$ specifies the bounded inevitability of p, i.e., p must hold along all paths whose cumulative duration satisfies I. Thus, the RTCTLC formula:

1. $\mathrm{AG}(\mathit{payed} \to A\mathrm{F}_{[0,4)}\mathit{delivered})$ specifies that whenever the Buyer pays for the goods, then the Seller will deliver the goods within cumulative duration of 3 days.
2. $\mathrm{AG}(\mathit{delivered} \Rightarrow (\mathrm{EF}_{[0,15)}\mathit{goodsOk} \vee \mathrm{EF}_{[0,15)}\mathit{goodsNotOk}))$ specifies that whenever the Seller ships the goods, then the Buyer accepts or rejects the goods within cumulative duration of 14 days.
3. $\mathrm{AG}_{[0,4)}(\mathrm{CC}_{\mathcal{S} \to \mathcal{B}}(\mathit{payed}, A\mathrm{F}_{[0,4)}\mathit{delivered}))$ specifies that along all paths within cumulative duration of 3 days the Seller $\mathcal{S}$ commits to the Buyer $\mathcal{B}$ to ship the requested goods within cumulative duration of 3 days if $\mathcal{B}$ has sent the agreed payment.

4. $\mathrm{AG}_{[0,4)}(Fu(\mathrm{CC}_{\mathcal{S}\to\mathcal{B}}(payed, A\mathrm{F}_{[0,4)}delivered)))$ specifies the fulfillment of the above Seller's commitment.
5. $\mathrm{AG}_{[0,4)}(\mathrm{CC}_{\mathcal{S}\to\{\mathcal{E},\mathcal{B}\}}(payed, A\mathrm{F}_{[0,4)}delivered))$ specifies that along all paths within cumulative duration of 3 days the Seller $\mathcal{S}$ commits to both to the Escrow $\mathcal{E}$ and to the Buyer $\mathcal{B}$ to ship the requested goods within cumulative duration of 3 days if $\mathcal{B}$ has sent the agreed payment.
6. $\mathrm{AG}_{[0,4)}(Fu(\mathrm{CC}_{\mathcal{S}\to\{\mathcal{E},\mathcal{B}\}}(payed, A\mathrm{F}_{[0,4)}delivered)))$ specifies the fulfillment of the above Seller's commitment.
7. $\mathrm{AG}(goodsNotOk \Rightarrow \mathrm{CC}_{\mathcal{E}\to\mathcal{B}}(returnGoods, \mathrm{AF}_{[0,3)}refund))$ specifies that along all paths if the Buyer is not satisfied, then the Escrow commits to the Buyer to refund the deposit within cumulative duration of 2 days under condition that the Buyer has returned the goods to the Seller.

As a second example, consider a set of n couriers (agents) working for a courier company, the work schedules of which are required to satisfy the property of k-bounded fairness, i.e., each courier should be scheduled for the new order at least once within cumulative duration of k hours and once she/he commits to deliver the Parcel within cumulative duration of no longer than k hours, she/he should fulfill her/his commitment on time. Let $p = deliverParcel$ be a proposition. This can be expressed by the RTCTLC formula:

$$\forall_{i=1}^{n}(\mathrm{AF}_{[0,k)}C_i \wedge \mathrm{EF}_{[0,k)}(\mathrm{C}_{C_i\to Cus}p))\wedge \\ \forall_{i=1}^{n}\mathrm{AG}(\mathrm{Fu}(\mathrm{C}_{C_i\to Cus}p) \Rightarrow \mathrm{AXAF}_{[0,k-1)}C_i),$$

where C_i indicates that courier i is scheduled for supply deliveries and Cus denotes the customer. The first set of conjuncts ensures that each courier is scheduled for supply deliveries within cumulative duration of k hours and she/he commits to deliver the Parcel within cumulative duration of no longer than k hours. The AG conjuncts ensure that, once courier fulfilled her/his commitment, she/he must be scheduled for the next supply deliveries again within cumulative duration of k hours.

4 Conclusion

We have shown how to extend the quantitative conditional commitment logic RTCTL^{CC} [6] to the group quantitative conditional commitment logic RTCTLC. The RTCTLC logic is suitable not only for reasoning about conditional commitments and their fulfillments of a single real-time agent but also for reasoning about conditional commitments and their fulfillments of group of agents.

We have also shown how to define a semantics of RTCTLC over the duration communication interpreted systems that allows for arbitrary durations over the global transitions. Thereby, we are able to reason about different levels of temporal deadlines and to reduce extra verification work resulting from the use of unit measure steps.

As future work, we plan to develop a new model checking algorithm for the whole logic and a new bounded model checking algorithm for its existential version.

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