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Model checking probabilistic social commitments for intelligent agent communication

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ABSTRACT

Interaction among autonomous agents in Multi-Agent Systems (MASs) is a key aspect for agents to coordinate with one another. Social approaches, as opposed to the mental approaches, have recently received a considerable attention in the area of agent communication. They exploit observable social commitments to develop a verifiable formal semantics through which communication protocols can be specified. Developing and implementing algorithmic model checking for social commitments have been recently addressed. However, model checking social commitments in the presence of uncertainty is yet to be investigated.

In this paper, we propose a model checking technique for verifying social commitments in uncertain settings. Social commitments are specified in a modal logical language called Probabilistic Computation Tree Logic of Commitments (PCTLC). The modal logic PCTLC extends PCTL, the probabilistic extension of CTL, with modalities for commitments and their fulfillments. The proposed verification method is a reduction-based model checking technique to the model checking of PCTL. The technique is based upon a set of reduction rules that translate PCTLC formulae to PCTL formulae to take benefit of existing model checkers such as PRISM. Proofs that confirm the soundness of the reduction technique are presented. We also present rules that transform our new version of interpreted systems into models of Markov Decision Processes (MDPs) to be suitable for the PRISM tool. We implemented our approach on top of the PRISM model checker and verified some given properties for the Oblivious Transfer Protocol from the cryptography domain. Our simulation demonstrates the effectiveness of our approach in verifying and model checking social commitments in the presence of uncertainty. We believe that the proposed formal verification technique will advance the literature of social commitments in such a way that not only representing social commitments in uncertain settings is doable, but also verifying them in such settings becomes achievable.

Introduction

Nowadays, the use of distributed environments to solve complex real world problems using entities called agents is on rise [44,8]. Communication is a fundamental aspect for these autonomous agents to coordinate with one another to solve fuzzy problems that are difficult for an individual agent to tackle [43]. This communication has been recently modeled by means of communicative social commitments [3,17]. As opposite to the mental approaches such as [64]—which focus on the minds of interacting agents—, social commitments proved to be a powerful representation for agent interactions. They, in fact, provide a social semantics that abstracts away from the agents internal states and offers social and observable meaning to agent messages exchange. Social commitments are agreements between two agents, namely *debtor* and *creditor*, in which the debtor engages towards the creditor to bring about a certain property [53]. Commitments result from communicative actions between the interacting parties. That is, agents create commitments and manipulate them through the protocol they use [10]. The manipulation of commitments via some operations (or actions) such as *creation*, *discharge*, *cancellation*, and *delegation* is indeed a vital element that captures the systems dynamics.

In order to represent and reason about social commitments, commitment logics that extend CTL (Computation Tree Logic), LTL (Lineal Temporal Logic), and CTL* (superset of CTL and LTL), have been proposed [52,26,48,57,6]. However, current logics are merely related to specifying and verifying social commitments in MASs

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where there is no use of randomization, and no presence of stochastic behaviors. That is, they assume an absolute, non-probabilistic running of the system. Unfortunately, this is not always the case. Heterogeneous and autonomous intelligent components in agent societies make it challenging to precisely analyze random or unreliable agent behaviors because their actions are based on observing the environment changes and in many situations, agents cannot observe all the changes in the environment as each agent can only have a partial view of other agents' behaviors [40]. In such cases, agents make estimations about the observable world as part of their autonomous decision making processes. Therefore, when the system being modeled is an open system, i.e., interacts with an environment, then uncertainty in the transitions may arise due to imperfect information about the environment [58,39,32]. Consequently, the problem of verifying social commitments is made more complicated by the presence of transition uncertainty which makes agents uncertain about the effects of their actions on their peers and not fully aware of the situations other agents are encountering. Moreover, from the communication perspective, commitments themselves are likely to be subject to probabilistic events. Xuan and Lesser [65] have highlighted some sources of uncertainty that make a commitment between two agents probabilistic:

1. The first source of uncertainty is related to the committed agent's action(s). That is, debtor's action(s) might not always lead to the fulfillment of the commitment.
2. The second source comes from the agent decision process. Debtors beliefs and desires might change such that continuing to pursue fulfilling the commitment for others becomes irrational. Committed agents beliefs about the commitment context include, for example, the degree that the agent to whom the commitment was made is still relying on its fulfillment. To the creditor, this can cause problems because its action(s) may depend on the honoring of the commitment by the debtor.
3. The third form of uncertainty comes from the incomplete knowledge of the debtor about the creditor or about the environment within which the agent interacts.

Motivation

As mentioned earlier, current proposals to verify social commitments in MASs assume typical settings in which agents behave in an ideal manner, and consequently commitments among communicating parties are treated under the assumption of certainty. However, in reality, one cannot assume that all autonomous agents will behave as expected. To motivate our study of modeling and verifying social commitments in the face of uncertainty, we use situational examples that arise in practical settings such web-based systems and mobile applications.

Example 1. Let us consider the Online Shopping System [27] which aims at providing services for purchasing online items. In the web-based Online Shopping System, customers can request to purchase one or more items from the supplier. Having selected an item, the customer commits towards the supplier to pay in order for the request to take place. Once the order is paid, the supplier confirms the order, and commits to deliver the requested item and enters a planned shipping date. Finally, when the order is shipped, the customer is notified. Because of the uncertainty associated to the underlying infrastructures of both commitments (i.e., the internet through which the payment is made and the transport system used for the delivery of purchased goods), there is no guarantee that these commitments will be fulfilled. Therefore, reasoning about and verifying the commitments to pay and to deliver have to be tackled with probability in mind so that the degree of fulfilling each commitment can be measured.

Example 2. In the field of mobile applications which are probabilistic in nature, addressing social commitments should be paired with the consideration of uncertainty of transitions and commitments. Let us consider a simple scenario where a receiver agent and a sender agent have an agreement, in which the receiver agrees to pay the sender in return of the delivery of a requested service. This can be represented as a social commitment, in which the receiver will be committed to the sender to pay upon obtaining the requested service. In such a scenario, because of the presence of stochastic behavior in mobile applications, the commitment to pay is not going to be surely satisfied.

The scenarios described above cannot be represented by existing conventional commitment logics because of the uncertainty aspect in both systems. Consequently, they cannot be verified. To cope with the situation, the need for a probabilistic logic that accounts for uncertainty, such as PCTLC [55] which we have previously proposed to address social commitments in the presence of stochastic behavior, and a probabilistic model checking procedure, as the one we are proposing in this paper to verify properties expressed in PCTLC, occurs. Therefore, the aim of this paper is to introduce a formal and fully automatic model checking technique for agent interactions captured using social commitments where uncertainty is a key factor.

Contributions

The contributions of this paper are twofold. First, we introduce a formal and fully automatic, probabilistic model checking technique for probabilistic commitment-based agent interactions. We model probabilistic MASs by extending the original formalism of interpreted systems introduced by Fagin et al. [19]. This extension considers agents uncertainty and their communication abilities. Properties to be verified (i.e., social commitments) are specified using the probabilistic logic of commitment PCTLC which we have previously proposed in [55]. The introduction of PCTLC logic was driven by the fact that current probabilistic temporal logics such as PCTL [29] and PCTL* [1] do not consider neither commitments nor agent communication. PCTLC extends PCTL with modalities for commitments and their fulfillments. Our proposed verification method is a reduction-based model checking technique and consists of transforming the problem of model checking PCTLC into the problem of model checking PCTL.

Second, we implement the proposed model checking approach as a model checker on top of the PRISM model checking tool,[1] and then apply it on a concrete case study, namely Oblivious Transfer Protocol [50] from cryptography domain. The PRISM tool is widely used for checking probabilistic specifications over probabilistic models. The specifications can be expressed either in the probabilistic computation tree logic (PCTL) or in the continuous stochastic logic (CSL) [2,21]. The models can be described using the PRISM language as Discrete-Time Markov Chains (DTMCs), Continuous-Time Markov Chains (CTMCs), Markov Decision Processes (MDPs), or Probabilistic Timed Automata (PTA).

Fig. 1 gives an overview of the whole framework, which consists of three parts. Part 1 (Logic part) presents the probabilistic logic PCTLC that we have proposed in [55] to reason about and specify social commitments employed in stochastic systems. Part 2 (Reduction part) and part 3 (Implementation part) represent the main contributions of this paper. Concretely, in the second part we reduce the problem of model checking PCTLC to the problem of model checking PCTL [29] so that the use of PRISM is made possible. As argued in [17], the main advantage of reduction techniques

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[1] http://www.prismmodelchecker.org