A Semi-Automatic Framework for the Design of Rational Resilient Collaborative Systems
Technical Report

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***Abstract*—Collaborative systems (e.g., P2P instant messaging, file sharing, live streaming applications) constitute the largest traffic of today's Internet. Common to all these systems is the assumption that, in return to the service offered by the collaborative system, users are willing to participate by sharing their resources with others. However, in practice, these systems suffer from *rational* users, i.e. users that benefit from the system without contributing their fair share to it. A number of solutions have been devised in the literature to deal with the problem of rational users in collaborative systems. However, most of these solutions are tailored to specific systems and thus lack flexibility and re-usability. In this paper, we propose *RACOON*, the first framework for RAtional resilient COllabOrative system desigN. *RACOON* relies on an extensible model that allows a system designer to specify the protocol steps and the different types of rational users he wants to consider. Furthermore, *RACOON* relies on game theory to reason on the behaviour of rational users. Finally, *RACOON* includes a simulation module that allows performance-oriented tuning of the system. Throughout the paper, we show how we used *RACOON* for the design of a rational-resilient, collaborative live-streaming application. Performance evaluation realised on one hundred real machines shows that the configuration proposed by *RACOON* allows all users to visualise a quality stream even in presence of rational users.**

I. Introduction

According to numerous studies (e.g., [9], [20], [5]), collaborative systems, also called peer-to-peer systems, account for the largest traffic of today's Internet. These systems include P2P instant messaging and voice over IP (e.g., Skype), P2P file sharing (e.g., Ares, BitTorrent, eDonkey), P2P live streaming (e.g., P2PTV, PPLIVE). The success of these systems mainly resides in their attractive properties among which the robustness to failures, the scalability to millions of users and the un-necessity to maintain costly dedicated servers as cost is shared among the participating users.

Common to all these systems is the assumption that, in return to the service offered by the collaborative system, users commit to sharing their (communication and computational) resources with others. However, in practice, these systems suffer from *rational* users, i.e. users that benefit from the system without contributing their fair share to it.

A number of solutions have been devised in the literature to deal with the problem of rational users in collaborative systems. Most of these systems rely on game theory by including incentives for rational users to collaborate with other users. Examples of such systems include rational-resilient live streaming [12], [6], rational-resilient anonymous communication [23], [3], rational-resilient spam filtering [2]. To design these systems, experts perform a manual analysis of all the possible rational deviations. Then, they augment the original protocol with incentives in such a way that it is not in the interest of rational users to deviate from the system specification. However, these systems suffer from a number of limitations. First, the analysis of rational deviations and the integration of the corresponding incentives are performed *manually* by the system designers, which is complex and error prone. Second, these systems are *hardly extensible*. Indeed, any modification in the original system requires to rethink the system as a whole, as modifications may introduce new rational deviations. Third, these solutions often *lack flexibility* as designers often assume that all rational users follow the same rationality model (i.e. they all behave similarly in the same conditions). Finally, in order to force rational users to always stick to the protocol specification, most of existing solutions heavily rely on cryptographic-based fault-detection mechanisms, which results in *poor performance*.

In this context, the challenge is to devise a framework to assist system designers in the performance-oriented design of robust and flexible rational resilient distributed systems.

In this paper, we embrace this challenge and propose *RACOON*, the first framework for RAtional resilient COllabOrative system desigN. To reach this objective, *RACOON* is composed of three parts. First, *RACOON* includes an extensible model that allows a system designer to describe the interaction patterns between users using state machines, and the different types of rational users he wants to consider. This model also allows a system designer to plug inspection mechanisms at specific points of the protocol in order to verify whether users participating to the protocol effectively stick to its specification or not. Second, *RACOON* includes a game theoretic module that allows reasoning on the behaviour of rational users when the latter are confronted to the inspection mechanisms. Third, *RACOON* includes a simulation module that uses the game analysis to provide the designer with performance-oriented guidelines for the fine tuning of its system (e.g., the penalty/rewards that users obtain when their behaviour appears as faulty/correct after inspection).

Throughout the paper, we show how we used *RACOON* for

the design of a rational-resilient, collaborative live-streaming application. Performance evaluation realised on one hundred real machines shows that the augmented system proposed by *RACOON* allows all users to visualise a quality stream in presence of rational users.

The remaining of the paper is organized as follows. First, Section II presents the problem statement and the goals and non-goals of our framework. Then, Section III presents the overview of *RACOON* while Section IV presents its detailed description. Further, Section V presents the performance evaluation of *RACOON*. Finally, Section VI discusses related work, and Section VII concludes this paper.

II. Problem statement, Goals and Non-Goals

Collaborative systems are systems in which users cooperate to realise a mutually beneficial service (e.g., overlay routing [8], cooperative backup [14], file sharing [24], live streaming [12], [6]). In addition to classical failures (e.g., crash of machines, malicious users), collaborative systems are subject to *rational behaviour*, i.e. users that benefit from the system without contributing their fair share to it. The rationality of a user is often defined by a utility function, i.e. a mathematical representation of its preferences (e.g., minimizing its bandwidth consumption) over a set of behavioural choices (e.g., replying or not replying to a given request).

In this context, our aim is to propose a framework to assist system designers in the design and evolution of collaborative systems that are robust to rational users.

To better illustrate the objectives of our framework, let us consider a simple protocol $P1$ in which a user $u0$ sends a request message $m0$ to a user $u1$. Upon receiving $m0$, $u1$ performs some local computation and replies to $u0$ by sending a message $m1$. In $P1$, the rationality of users can take different forms. For instance, a rational user $u1$ can omit to send a response to $u0$ to save bandwidth (i.e. communication-related rationality). Alternatively, to avoid being harassed by $u0$ which might retransmit its request, $u1$ can skip the computations necessary to compute $m1$ and send instead a wrong response to $u0$ (i.e. computation-related rationality). These two different types of rationalities require the system designer to include different types of incentives/counter measures. Furthermore, while it is often assumed in the literature that all rational users have the same rationality, the reality is different as many different types of rational users can co-exist in a collaborative system.

The first objective of RACOON is thus to allow a system designer to model different types of rationalities and to automatically propose incentives/counter measures adapted to each of them.

A classical solution to reason on rational behaviours is to rely on game theory and specifically on the concept of Nash equilibrium [17]. This concept defines a strategy for each participant in the game (i.e. each user in the collaborative system) from which there is no benefit in deviating. Many collaborative systems are thus designed (from scratch) to be a Nash equilibrium (e.g., [12], [2], [3], [13]) by embedding incentives on each protocol step in such a way that it is not in the interest of rational users to behave rationally. However, these systems are hardly extensible as any modification in the original protocol may introduce new rational deviations and thus break the Nash equilibrium.

The second objective of RACOON is thus to introduce automation in the process of devising the rational resilient system. This enables more robustness and the easy evolution of the resulting collaborative system.

Among the classical incentives to force rational nodes to stick to a protocol is to integrate inspection mechanisms (e.g., [7], [1]). For instance, in the protocol $P1$ introduced above, each user could be associated with a *secure* log in which it writes all its interactions with other users. Periodically, each user can inspect the log of its partners to verify that their behaviours correspond to a correct execution of the protocol. However, these mechanisms are very costly especially if inspections are performed regularly (e.g., to deter faults faster). Moreover, a realistic collaborative system should accept the presence of some uncooperative behaviours. For example, users may deviate in good faith, because of limited resources or inexperience. In these situations, it may be beneficial to relax the security properties of the system.

The third objective of RACOON is thus to allow the system designer to set up inspection mechanisms according to the rationality models he wants to consider on the one hand and to the performance he wants to reach on the other hand.

Finally, we also list some non-goals in order to help position our contribution. First, we do not aim at outperforming established context-specific solutions for dealing with rational users. Instead, we aim at providing software designers with a framework to easily design and maintain a rational resilient collaborative system. Second, *RACOON* does not generate executable code. Third, *RACOON* does not enable on-line analysis of software systems. All the analysis performed by *RACOON* are done offline at design time.

III. *RACOON* Overview

RACOON reaches the objectives specified above by relying on classical building blocks for the design of rational-resilient collaborative systems. Specifically, *RACOON* specifies the communication protocols among users using finite state machines. It predicts rational behaviours using game theory. Further, it makes deviations unprofitable using inspection mechanisms. Finally, it tests the achievement of performance and security requirements using simulations.

Fig. 1 shows the four phases that a system designer follows when using our framework. The first phase, i.e. the *specification* phase, is manually performed by the system designer. In this phase, the designer specifies the system following the model presented in Section IV-A. This model allows the specification of the interaction patterns between users, the types of rationalities investigated, and the configuration of the security mechanisms. Once the first phase has been completed, then *RACOON* proceeds automatically. The second phase depicted in the figure is the *augmentation* phase. In this phase,

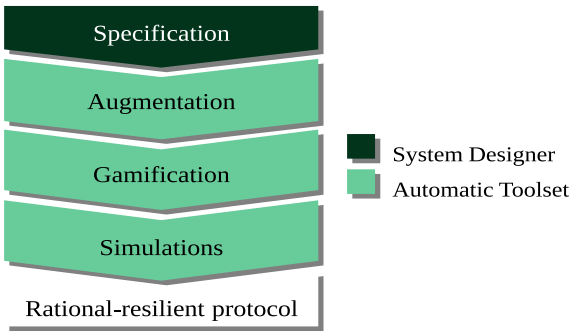
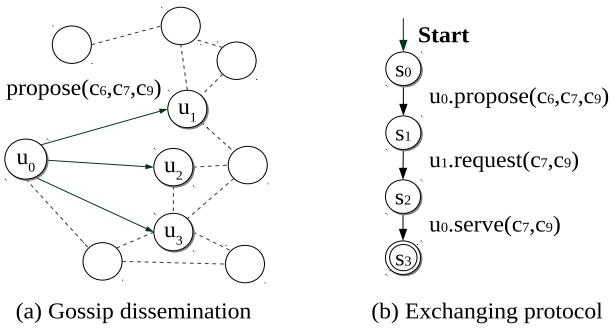


Fig. 1: The four phases of the *RACOON* framework.



(a) Gossip dissemination (b) Exchanging protocol

Fig. 2: Gossip-based protocol for chunks dissemination.

the specification produced by the designer is automatically augmented with rational deviations. The automatic generation of deviations applies the model of rationality defined by the designer in the specification phase (see Section IV-B1). The original specification is also augmented with the security modules, which are: (i) inspection methods to expose rational deviations, and (ii) an incentive system to reward users when they behave cooperatively, and punish them when they do not. We present these modules in Section IV-B2. Then, the framework proceeds with the third phase, i.e. the *gamification* phase, which aims at predicting the behavioural choice of a user in a certain system set-up. In other words, *RACOON* estimates the most favourable behaviour among all the possible candidates from the augmented protocol. We achieve this with a game theoretic approach. Game theory is indeed the most appropriate tool to predict the interactions among rational decision-makers. The *gamification* phase carries out the game theoretic analysis by transforming the augmented protocol into a suitable game representation (see Section IV-C1). The analysis leads to a Nash Equilibrium [17], which we use to predict rational behaviours. Finally, the last phase, i.e. the *simulation* phase, tests whether the rational-resilience and performance requirements are satisfied. The simulator uses the augmented protocol and the game theoretic predictions to produce a set of measures. The designer compares these measures to determine if the system specification is worth implementing or not. If not, *RACOON* provides insights to help the system designer to find the right parameters to meet its performance requirements.

IV. *RACOON* Detailed Description

In this section we present *RACOON* in detail, following the sequencing of phases introduced in the previous section. To better illustrate the various parts of *RACOON* with concrete examples, we start by introducing a case study, which is the design of a P2P live-streaming application.

Case Study: P2P Live Streaming

The P2P live-streaming system consists of a stream source and an audience of n users (peers). The source of the streaming session encodes the video, cuts it into pieces (chunks) and periodically broadcasts c of them to a set of users. At each period of time, the broadcast reaches a fraction a of the users in the network. We assume the source is cooperative, while a proportion r of users can be rational. Each user must receive chunks within a deadline d to be played out (play-out delay). An expired chunk is equivalent to a lost chunk, because it can not be reproduced. In order to support the media distribution process, users share chunks with each other using a content dissemination protocol. The upload bandwidth of users is limited to b chunks/round. We consider the three-phase gossip protocol used in [6]. Every p rounds (which is the period), users establish a partnership with f others selected uniformly at random. Then, they propose their not expired chunks to all of them. Fig. 2(a) shows the propose phase, where user u_0 sends a list of chunk's identifiers (c_6, c_7, c_9) to its 3 partners (u_1, u_2, u_3). As soon as the `propose` has been received, the partners request the chunks they miss (`request` message). Eventually, the proposing user sends the payload of the requested chunks (`serve` message). Fig. 2(b) illustrates the state machine of the above protocol, where user u_1 requests the chunks 7 and 9 from u_0. The label of each transition defines the user's ID, the name of the method invoked and the ID of the message sent.

A. Specification

In this phase, the designer defines the collaborative system. The framework provides a specification model to guide this task. The output is an instance of the specification model characterizing the target collaborative system.

The designer specifies its collaborative system following the UML diagram depicted in Fig. 3. Each element in this diagram describes characteristics or requirements of the system. We classify them in four logical areas: the *User* domain, the *Rationality* domain, the *Security* domain, and the *System* domain. The white elements in Fig. 3 are application dependent, whereas the coloured ones can be re-employed in different contexts. This approach improves the reusability, and enables the automation of the next phases of the framework. The specifications are encoded as a machine-readable XML-based format. The XML Schema of each element can be found in the companion technical report [11]. In the following, we detail the four specification domains.

User domain defines the user and the interaction protocols

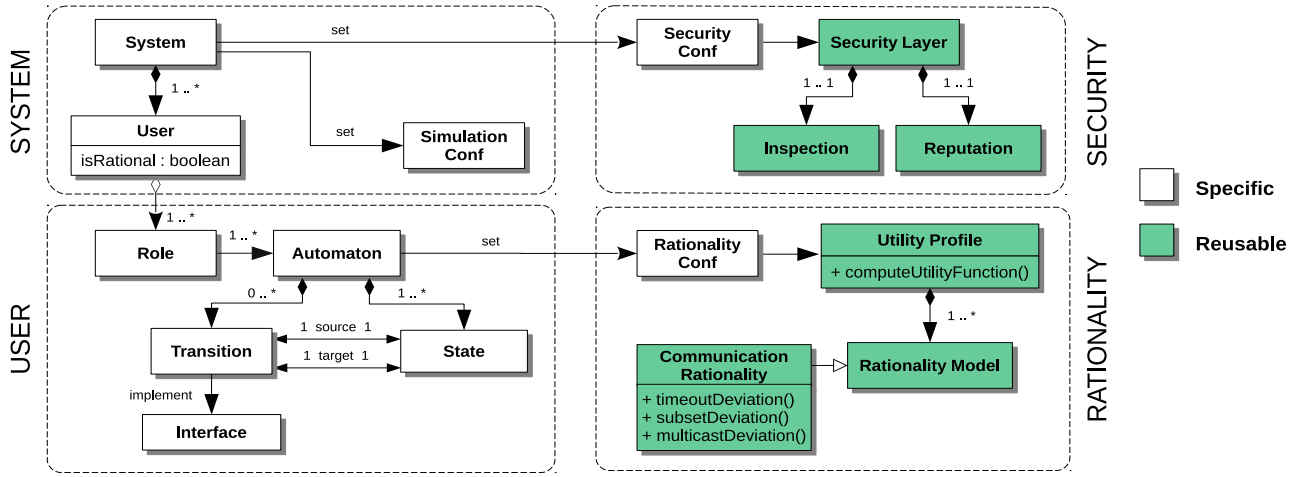


Fig. 3: *RACOON* Specification Model of a collaborative system.

in which it participates. The *Role* element describes the part that a user may undertake in a protocol. For instance, in our case study, one can participate to the gossip protocol as a sender or as a receiver. The interaction among users is represented as deterministic finite *State Machine*, like the one shown in Fig 2(b). We assume no loops in the state machine. A *State* represents a stage of the protocol, while *Transition*s are the operations (e.g., communications or computations) that enable its evolution. An operation corresponds to the invocation of a set of methods. The *Interface* element collects all the methods that a transition must implement. The same method can describe the functionality that a user provides or uses, according to the role that it plays in the protocol. For example, the method `propose` in Fig. 2(b) is provided by u_0 (sender) and used by u_1 (receiver). The designer also declares possible relationships among contents, and provides their XML Schema type.

Rationality domain The rationality of a user is defined by its utility function, that is specified in the *Utility Profile* element. Note that the same user may have several *Utility Profile*s, one for each role it undertakes in a certain protocol. In order to simplify the definition of a utility function, we propose to build it by enabling *Rationality Model* elements, which identify specific types of rational behaviours. This encourages the reuse of already defined elements, and simplifies the analysis of the system under new rationality assumptions. The *Utility Profile* and the *Rationality Model*s are independent from the specific application. Finally, in the *Rationality Conf* element the designer specifies the models of rationality to activate, along with the types of deviation to generate. For our case study, we have implemented the *Communication Rationality* model, a specialization of the *Rationality Model* element. We discuss it in Section IV-B1.

Security domain It specifies the modules that provide resilience from rational behaviours. They are defined as implementation of the abstract *Security Layer* element, so that they can be easily replaced with different modules. In this paper, we use the *Inspection* module to detect deviations, and the *Reputation* module to enforce cooperation. The *Security Conf* element allows to configure both. We defer a description of the security modules and their parameters in Section IV-B2.

System domain It specifies system specific information, which are necessary to set-up the simulations. In particular, the designer specifies the proportion of rational users in the system, possibly all of them. In our use case, some example of these are the number of users in the system, the length of the stream, and the probability of message loss in each communication. The code in Listing 1 presents an extract of the User domain specification of our case study. The complete specification awaits in the companion technical report [11].

B. Augmentation

The goal of this phase is to include rational behaviours and security mechanisms into the protocol's representation. The result, called augmented protocol, details how the collaborative system changes in presence of rational users.

1) Rational Deviations: A rational deviation is a violation of the protocol that aims at maximizing a utility function. In *RACOON*, utility functions are defined by activating a *Rationality Model* created by the designer. This is a set of algorithms that realize a specific model of rationality (e.g., saving bandwidth consumption, reducing computational costs). Each algorithm takes as input the *User domain* specification of the system, and describes the procedure to derive rational deviations. *RACOON* provides an automatic tool that executes the algorithms of the *Rationality Model*s enabled by the designer. This process results in the generation of new states and transitions, which the automated tool adds to the original state machine. Notice that each new transition is created along with a new interface, which contains at least one deviation. The resulting state machine is called *augmented automaton*, where every execution path (i.e. the path that connects the initial state to a final state) represents a possible user's behaviour.

Listing 1: User domain specification of the state machine shown in Fig. 2(b).

```
<userDomain>
    <roles>
        <role name="sender" />
        <role name="receiver" />
    </roles>
    <states>
        <state name="s0"> <initial /> </state>
        <state name="s1" />
        <state name="s2" />
        <state name="s3"> <final /> </state>
    </states>
    <transitions>
        <transition name="t0" interface="i0"
                    fromState="s0" toState="s1">
            <fromRole>sender</fromRole>
            <toRoles>
                <toRole>receiver</toRole>
            </toRoles>
        </transition>
        ...
    </transitions>
    <interfaces>
        <interface name="i0">
            <methods>
                <method name="propose">
                    <content name="m0" type="list" />
                </method>
            </methods>
        </interface>
        ...
    </interfaces>
</userDomain>
```

We provide as part of the *RACOON* framework the specification of the *Communication* rationality model. Its utility function aims at minimizing the communication costs for rational users. We define communication costs in terms of bandwidth consumption, which depends on the length and on the type of the transmitted contents. From the three-phase gossip protocol of the case study, we can identify three rational deviations consistent with this model: (d1) decreasing the number of partners, so that a sender receives a lower number of requests, (d2) proposing less chunks than what a sender holds, and (d3) sending only a subset of the requested chunks. Based on these insights, we have designed three rational deviations intended to reduce communication costs:

i) Timeout Deviation. The user does not perform the prescribed operation within the necessary time frame. For example, it does not send any chunks proposal, or does not reply to a request. The algorithm: for each non-final state s of the protocol, checks whether it has at least one outgoing transition that executes a legal timeout. If so, skip to the next state. Otherwise, create a new final state s_{to}, and connect it with s by a timeout deviation.

ii) Subset Deviation. The user sends only a subset of the legit content. This behaviour covers the deviations (d1) and (d2) described above. The algorithm: for each non-final state s of the protocol, consider the set of its outgoing transitions T. If a transition $t \in T$ transmits a content with a complex type (according to the XML Schema type definition), then create a new state s_{sub} and connect it with s by a subset deviation t_{sub}. The content transmitted in t_{sub} must be a subset of the legit one. Fig. 4 illustrates the procedure. The illegal states are represented with filled circles, and labels of deviations are in italics. Note that the message sent by a subset deviation is indicated by an exclamation mark (!) before its ID.

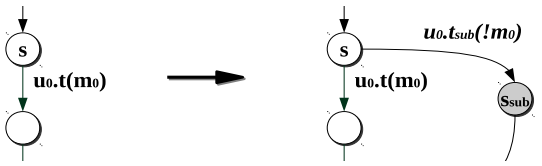


Fig. 4: Generation of the *subset deviation* t_{sub}.

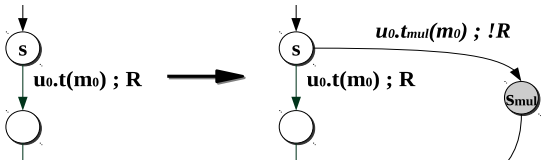


Fig. 5: Generation of the *multicast deviation* t_{mul}.

iii) Multicast Deviation. The user does not perform a certain operation with all the prescribed partners, but only with a subset of them. For instance, a user can decrease the size of its partnership, like described in (d3). The algorithm: for each non-final state s of the protocol, consider the set of its outgoing transitions T. If a transition $t \in T$ sends a message to more than one recipient, then create a new state s_{mul} and connect it with s by a multicast deviation t_{mul}. The recipients of t_{mul} must be less than the legit ones. The procedure is shown in Fig. 5. For reason of clarity, we write the recipient of a transition at the end of each label, after a semicolon (;). The legit set of recipients is indicated with R, while the non-legal one with $!R$.

Notice that once an illegal state is created, *RACOON* updates its connections with the other states of the automaton. The generality of the algorithms makes the *Communication Rationality* model applicable to any collaborative systems. Fig. 6 shows the three-phase gossip protocol augmented with *timeout* and *subset* deviations. For clarity we do not represent multicast deviations. Consider for instance the state s_2. In the correct execution of the protocol, the user u_0 sends a list with the payload of the requested chunks (m_2) to user u_1. However, a rational user may also timeout the request, or serve a list with less chunks ($!m_2$). In both cases, the protocol terminates in an illegal state (s_{2t} and s_{2s}, respectively), and u_1 does not obtain what it requested.

2) Security Layer: RACOON forces collaboration by making rational users accountable for their actions. This is realized by employing a security layer, which seamlessly extends the logic of the original protocol. The security layer implements an inspection module to detect rational deviations, and a reputation module to assign positive or negative feedback on the reputation of users. The deployment of the security mechanisms on an *augmented automaton* results in an *augmented protocol*, which is also the outcome of this phase of

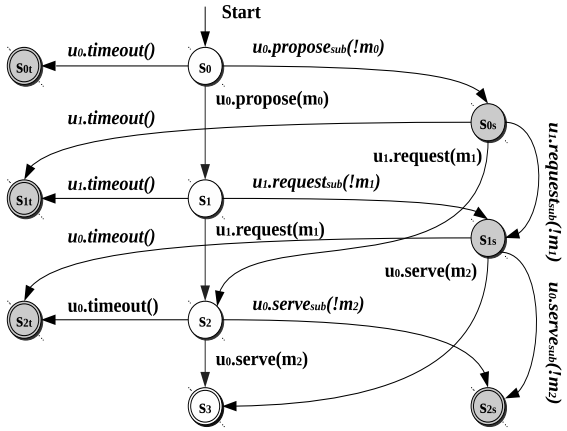


Fig. 6: The *augmented automaton* of the state machine shown in Fig. 2, augmented with *timeout* and *subset* deviations.

the framework.

Inspection: We propose to build upon inspection mechanisms to detect and expose rational deviations in collaborative systems. In *RACOON*, each user maintains a *secure* log that keeps a record of its activities within the protocol (e.g., exchanged messages with other users). In the last years, many solutions that enforce accountability using secure logs, i.e. logs that are tamper-evident, have been proposed in the literature. We rely on the solution proposed in [7]. Note that the software developer can also decide to employ other inspection mechanisms, e.g., [1], [6].

In *RACOON*, users can periodically perform inspections of each other's logs, eventually detecting if and when a rational user has deviated from the protocol. To configure the inspection module, the designer specifies: (i) the role or the user that performs the inspection, (ii) the role or the user to inspect, (iii) the state of the augmented automaton where the inspection takes place, and (iv) the probability of inspection. Note that the simulation phase helps the designer to configure these parameters.

Reputation: We use reputation as an incentive mechanism to motivate users to adhere to the protocol. Specifically, each user is associated with a reputation value. This reputation increases when its log appears correct after an inspection performed by another user and decreases if a deviation is detected by the latter. The reputation value is stored locally in the security layer, and is distributed with a decentralized mechanism such as [16]. One may wonder why users should care about their reputation. The reason is that if the reputation goes below a fixed threshold, then the user is evicted from the system. Users are aware of the risk to be punished if they choose to deviate. Therefore, as the eviction is a credible threat, if their reputation is too close to the threshold they are more likely to cooperate. We also introduce an upper limit for the reputation value, to discourage users with high reputation to start deviating for many consecutive times. In Section IV-C1 we discuss how to integrate such mechanisms into the utility function. The designer can configure the reputation module by setting the range of values for the reputation.

C. Gamification

The augmented protocol is transformed into a game. A game theoretic analysis is then performed to predict the behaviour of rational users. Such prediction is the output of this phase.

We use game theory to assess the likelihood of rational deviations from the *augmented protocol*. In fact, game theory is the natural framework to model the interplay of rational users in competitive systems [19]. *RACOON* provides an automatic tool to transform any *augmented protocol* into a game. The tool also performs the game theoretic analysis, that reveals the expected behaviour of the rational users.

1) Game Mapping: We model a collaborative protocol as a non-cooperative game with complete information [17]. A non-cooperative game describes the interactions among rational decision-makers (players). A player represents a role played by a user in the protocol, and is associated with a set of possible actions. Each action corresponds to a method of the *augmented protocol*, possibly a deviation. As the *augmented protocol* defines a certain order of execution of methods, we map it into a game with sequential moves. When a player performs an action, it does not know if it is responding to a deviation unless it performs an inspection. The information available to a player at a given point in the game form an information set. The sequence of actions that a player executes in a game is called a strategy, while a set of joint strategies (one for each player) is called a strategy profile. A strategy profile is called a Nash Equilibrium (NE) if no player, when finding himself in that strategy profile, has incentive in deviating unilaterally from its strategy: a NE conventionally characterizes in game theory the expected behaviour from rational players [15]. Finite games (finite number of players, finite number of strategies) are granted to always have a NE [17]. The goal of a player is to follow the strategy that maximizes its utility function. The assumption of rationality requires that such choice takes also into account the potential strategies of other players. Indeed, all the factors of the game (i.e. players, order of moves, possible strategies, utility function) are common knowledge.

All these conditions result in a sequential game with complete but imperfect information, which is usually represented by its extensive-form, also called game tree [19]. *RACOON* derives the game elements from the *augmented protocol* specification. Table I summarizes the rules to map the latter into a game tree. For instance, a player in the game tree corresponds to a role played by a rational user in the augmented protocol. The utility $\bar{u}_i$ for player p_i while playing the strategy σ_i is a function of the operational costs incurred to implement the strategy and the incentives received from the security mechanisms. It can be expressed as:

$$\bar{u}_i(\sigma_i) = \sum cost_i(\sigma_i) + \gamma(oldRep_i, newRep_i),$$

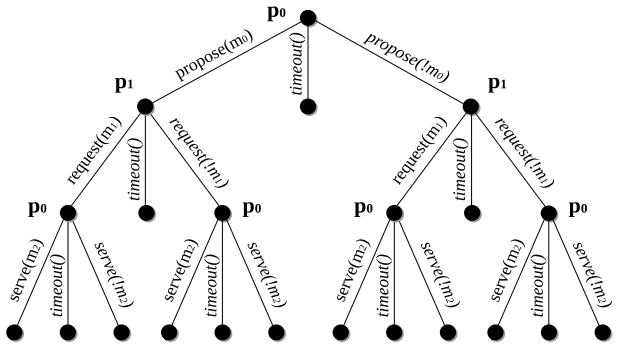


Fig. 7: The extensive-form game representation of the *augmented automaton* shown in Fig. 6.

Augmented Protocol	Extensive-form game
Rational User	Player
Non-final state	Internal Node
Final state	Terminal node
Transition	Edge
Execution path	Strategy profile
Inspection setup	Information sets

TABLE I: Correspondences between augmented protocol and extensive-form game

where γ integrates the reputation values into the utility function. The intuition behind γ is that the 'shadow of the future' affects the perception of today's utility. The function γ formulates such effect in terms of additional costs or discounts. More specifically, when a player expects a punishment (the new reputation $newRep$ is lower than $oldRep$), γ identifies two types of cost:

- Eviction cost: the cost for being expelled from the system, which is paid only if the new reputation is below a given threshold. It is conventionally set at a very high nominal value, since an eviction is the worst utility a player may have.
- Redemption cost: the cost for regaining the old reputation. It is the product between the profit margin of a deviation (i.e. the cost saved by performing a certain deviation) and the redemption time (i.e. the expected time during which the player must behave correctly).

In contrast, if a player expects a reward ($newRep$ is greater than $oldRep$), then the function γ identifies a cost discount. This is because the convenience of a future deviation becomes more important as the reputation value increases. In other words, the benefit of the profit margin of tomorrow is higher than the cost of possible punishments. Fig. 7 illustrates the result of the game mapping of the *augmented protocol* shown in Fig. 6. Each leaf of the game tree is associated with a pair of payoffs, one for each player. For reason of space, they are not reported in the figure. Moreover, details on the algorithm that augments the protocol with rational deviations are omitted but can be found in the companion technical report [11].

2) Game Analysis: The *gamification* tool of *RACOON* can integrate several solution concepts for the game theoretic analysis [18]. For the sake of simplicity, and without loss of generality, the solution concept we use for this paper is the Subgame-Perfect equilibrium (SPE) in pure strategies [19]. It is a refinement of NE for extensive-form games. Subgame perfection ensures that no player has an incentive to change the equilibrium strategy as the game progresses. We assume that if a game has a SPE, then all rational players will follow the equilibrium strategy. If no equilibrium in pure strategies is found, then we assume that rational players will withdraw from the protocol (worst case). To find the SPE of the protocols *gamified* in the previous step, *RACOON* uses Gambit[1], an open-source library of tools for game-theoretic analysis. The algorithm to find the SPE is described in [18].

D. Simulations

We test whether the augmented protocol achieves the designer's performance requirements. To this end, we simulate the system using the predictions of the gamification phase.

The solution of the *gamified* protocol represents a "snapshot" of the system evolution. In fact, it holds only for a particular configuration of factors (e.g., the security setting, the current reputation of players). Therefore, the predictive power of a single game solution is too narrow to give a full picture of the users' dynamics. The last phase of *RACOON* framework addresses this issue by adopting a simulation approach. Simulations provide a practical evaluation of the security configuration, by reproducing how users behave within a given system set-up. Another direct advantage of such pragmatic approach is that it enables to study how different degrees of tolerance to rational deviations affect the final outcome.

A prerequisite for the *simulation* phase is to have a simulation environment for the system under consideration. With this in mind, we have developed a Java-based simulator that supports cycle-based applications over a generic P2P overlay network. The *simulation* workflow proceeds in four steps:

1) Parse the system specifications and configure the simulation setup accordingly.
2) Partition the system dynamics into behavioural units. Each behavioural unit corresponds to the particular reputation setting in which two or more users may interact. Behavioural units are the building blocks to generate every possible evolution of the system.
3) *Gamification* of the behavioural units as independent games, which results in a broad range of game solutions. These represent the predictions of selfish users behaviours, that tell the simulator how to progress.
4) Run the simulation, while collecting the information that is relevant to the performance evaluation.

The simulation's result determines whether the configuration of the security modules is satisfactory or not. A satisfac-

[1]GAMBIT: http://sourceforge.net/projects/gambit/

tory configuration must guarantee good performance even in presence of rational users. If not, then the designer can set different security settings and restart the simulation. If instead the system achieves the desired performance, then the designer can implement the collaborative system that has been designed and tested using *RACOON*.

V. Evaluation

We present in this section the evaluation of our *RACOON* framework. This evaluation divides in three parts. In order to better understand the scope of the problem posed by the presence of rational users, the first part, presented in Section V-A, shows the impact of these users in the collaborative live streaming application introduced in Section IV. Then, the second part, presented in Section V-B, focuses on the effort required by a software developer to make the above live streaming application resilient to rational users using our framework. Furthermore, in this part, we show how *RACOON* helps the software developer to easily update its application if he wants to consider a new rationality model or change some protocol steps Guido ►*should we omit the latter, since we don't show how later?*◄. Finally, the third part, presented in Section V-C, shows how the simulation part of our framework helps the software developer in choosing the right configuration for its live streaming application considering a list of performance requirements. Also, in this part we show that the configuration chosen by the software developer after the simulation part, implemented and deployed on 100 users running on real machines, exhibits the expected performance.

A. Impact of Rational Users on the Live Streaming Use Case

To measure the impact of rational users on the live streaming use case presented in Section IV we implemented this application and deployed it on a Grid'5000 cluster[2] of 10 eight-core physical machines. Each machine is clocked at 2.5GHz with 32GB of RAM, and is interconnected with the others via a Gigabit switch. We then deployed 100 users, and we studied different proportions of rational users ranging from 0 to 100%. These users have two possible rationalities, according to the role they play in the protocol. A *receiver* performs only *subset* deviations, whereas a *sender* also performs *timeout* and *multicast* deviations. In fact, senders carry most of the cost of collaboration, but only the receivers benefits from it. We measure the percentage of video chunks lost by users on average. According to study performed in [21], if this value is lower than 3%, users do not notice any degradation in the quality of the received video. Fig. 8 presents the results of our experiment. We observe in this figure that, as expected, the percentage of lost chunks without any rational-resiliency mechanism (i.e. curve G5K w/o *RACOON*) increases as the percentage of rational users increases. Further, this curve shows that in presence of even 10% of rational users, the quality of the stream is unvisualisable for all users. In addition to this curve, Fig. 8 shows the performance of our rational-resilient live streaming application as simulated by *RACOON*

[2]Grid'5000: http://www.grid5000.fr

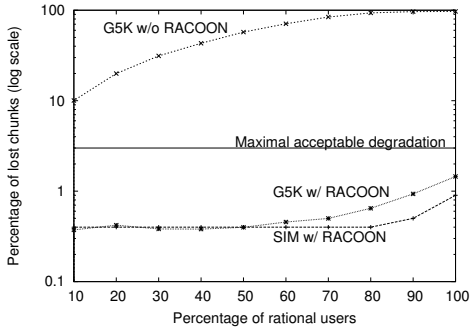


Fig. 8: Percentage of lost chunks as a function of the proportion of rational users.

(i.e. the SIM w/ *RACOON* curve), as well as a real implementation of it (i.e. the G5K w/ *RACOON* curve). These two curves show that, thanks to *RACOON*, we were able to build a rational resilient live streaming application in which even in presence of 100% rational users all users are able to visualise a quality stream. In the remaining of this section, we show how *RACOON* was used to reach this objective.

B. Using RACOON for the Design and Evolution of the Live Streaming Application

We now describe the effort required by a software developer to design, implement and maintain the rational resilient live streaming application corresponding to our case study using *RACOON*. Table II shows the size of the XML description, the size of the simulation code and the size of the real implementation that the software developer has to write to describe and implement its application. For each of these three parts, we distinguish between the number of lines that are specific to the use case application and those that are generic and thus reusable from one application to another. From this table, we observe that the amount of reusable code is at least of 40% (for the XML description) and can be as high as 83% (for the simulation part). This high degree of reusability is enabled thanks to the modularity of *RACOON*.

Lines of code	XML description	Simulator	Prototype
All	140	2500	3064
Specific	83	410	1118
Reusable	57	2090	1946
%tage reusable	40.7	83.6	63.5

TABLE II: Number of lines of code and percentage of reusable code in the XML description, the simulator and the prototype.

We now focus on the evaluation of the ability of *RACOON* in enabling software evolution. Let us consider that the software developer, which has initially designed its software by assuming a proportion of up to 50% rational users, wants to consider a proportion of 80% instead. Furthermore, let us consider that the designer, which has initially activated *timeout* deviations only for the role of *sender*, wants now to consider these deviations also for the role of *receiver*.

Using *RACOON*, performing the first modification requires changing one single line in the XML description of the

application. In particular, the designer has only to set the `rationalFraction` property to `0.8` in the following line:

```
<property name="rationalFraction">0.5</property>
```

Furthermore, adding the timeout deviation for the *receiver* role requires adding one line in the Rationality Domain part of the XML description. In the following, the bolder line is the only modification required:

```
<deviation name="timeout">
   <role>sender</role>
   <role>receiver</role>
</deviation>
```

After these two modifications performed on the XML description, *RACOON* proceeds automatically by updating the augmented protocol and the game analysis, which allows to automatically change the results of the simulation.

This shows that using *RACOON*, the software developer can very easily make its system evolve to adapt to changes into the environment (e.g., updating the rationality model, changing the protocol steps).

C. Building a Rational Resilient Live Streaming Application using RACOON

We show in this section how *RACOON* helps the software developer in choosing the right configuration for its application using the simulation module.

Let us consider that the software developer has fixed the following performance requirements for his rational resilient live streaming application:
(*Req1*): Correct nodes are not wrongly evicted by the system, even in presence of (up to 5% of) message loss due to disrupted networking conditions.
(*Req2*): The overhead of the protocol in terms of bandwidth consumption does not exceed 10% of the bandwidth consumed by the live streaming.
(*Req3*): Correct nodes do not lose more than 3% of video chucks, which ensures that they watch a good quality stream.

There are two parameters in the application that the developer can tune to get the expected performance. These parameters are: (1) *the penalty*, which is the value by which the reputation of a user is decreased if its log is inspected and detected as faulty; and (2) the *percentage of audits* that a receiver performs on a sender with whom it interacts.

To fix these parameters the software developer performs the following simulations, for which the results are depicted in Fig. 9. First, it starts by studying the impact of the penalty on the percentage of eviction of correct users in presence of 5% message loss. From Fig. 9(a), we can observe that the higher the penalty the higher the proportion of evicted correct nodes. This is due to the fact that with a high penalty, it is enough to be subject to the loss of one or two messages in order to be wrongly considered as behaving rationally. From this experiment, the software developer can decide to fix the value of penalty to 8 or lower as this value limits the percentage of evicted correct nodes to less than 1%, which matches its first performance requirement.

Using this value of penalty, the software developer can also notice from Fig. 9(b) that the percentage of evicted rational nodes is at least of 65% (if the probability to audit users is equal to 10%), which is satisfactory. From this curve, the developer can also notice that the higher the probability to audit users, the higher the percentage of evicted rational users. However, intuitively, the designer may be interested in the overhead of performing more inspections (in terms of bandwidth consumption). To help fixing the probability to audit users, the designer can refer to the results of Fig. 9(c), which show the overhead in terms of network traffic with respect to the probability to audit. From this figure the designer may decide to fix this value to less than 20% in order to meet its second requirement.

The last experiment (Fig. 9(d)) shows the quality of the stream perceived by correct users as a function of the percentage of rational users for different values of audit probability. From this experiment, the software developer can finally decide to fix the audit probability to 15%. Indeed, this value is enough to get all correct nodes receive a stream with less than 3% of missed chunks.

Summarising, using the simulations enabled by *RACOON*, the software developer decides to fix the value of the penalty to 8 and the audit probability to 15%, which allows to satisfy all its performance requirements. As discussed at the beginning of this section and shown in Fig. 8, the performance of the live streaming application when implemented with the above parameters and deployed in a real setting validate the choice prescribed by *RACOON*.

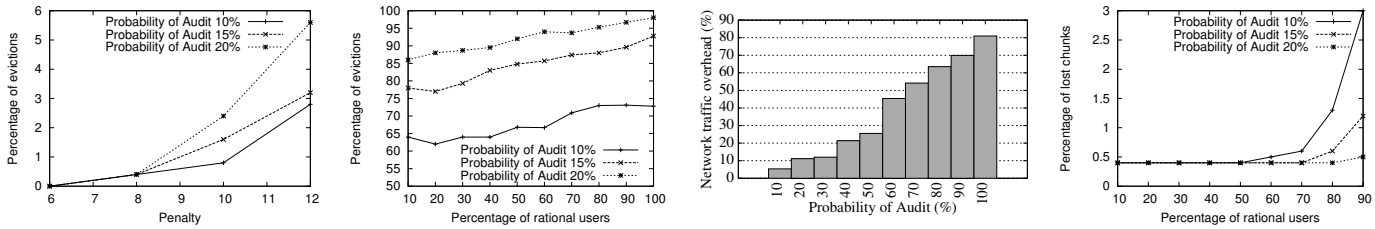
VI. Related work

There is a vast amount of literature on designing distributed systems. We approach this overview with our research objectives in mind: resilience to rational behaviours, support to system evolution, and good performance. Table III summarizes these objectives, along with the contributions of the works closest to ours. As we can observe, there is no existing solution that meets all the challenges. The *RACOON* framework does.

	Rationality	Evolution	Performance
Game Theory	√	-	-
Accountability	√	√	-
DSL	-	√	√
RACOON	√	√	√

TABLE III: Summary of the state-of-the-art solutions available to design rational-resilient collaborative systems.

Game theory is recognized as being a good framework to address rational behaviours [12], [2], [3], [13]. The aim of game theoretic approaches is to make cooperation the best rational choice, i.e. a Nash Equilibrium. Unfortunately, their solutions are tailored to specific applications, thus are extremely sensitive to changes in the system conditions. Another well-known criticism of game theoretic solutions concerns



(a) Percentage of evicted correct users. (b) Percentage of evicted rational users. (c) Audit overhead. (d) Percentage of lost chunks.

Fig. 9: *RACOON* results.

their performance, because of the strict requirements imposed by the equilibrium assumptions. For example, [12] provides good rational resilience (along with fault tolerance) in live-streaming application, but it suffers from high bandwidth consumption and low scalability [13]. The semi-automatic procedures adopted by *RACOON* overcome these limitations.

A rational deviation is a particular type of malicious behaviour. For this reason, accountability systems like [7] seem to be an acceptable solution for the rationality issue. Furthermore, the generality of their specification also meets the challenge of supporting the system evolution. The major pitfall of these approaches is that maintaining accountability incurs a non-negligible cost in terms of performance (i.e. high communication and computational costs of the monitoring system). On the contrary, *RACOON* enables to take performance requirements into account, finding the right compromise between them and rational resilience. Other shortcomings of accountability methods come from some strong assumptions about the system. For example, they require a quorum of collaborative users to be effective [7]. Further, they are not tolerant to message loss. Using *RACOON*, the designer can find proper solutions without relying on these assumptions.

Finally, several frameworks [22] and Domain-Specific Languages [10], [4] have been proposed in the literature to ease the task of designing and maintaining a distributed system. It is well known that domain-specific approaches can yield to high performance results. Nevertheless, to the best of our knowledge, none of these solutions considers the problem of rational behaviours. The game theoretic approach of our framework meets this challenge.

VII. Conclusion

In this paper we have presented *RACOON*, a framework for semi-automatic game-theoretic analysis of collaborative systems. *RACOON*'s objective is to allow the designer to automatically design a rational-resilient version of a collaborative system. For this, *RACOON* augments a given protocol specification with possible rational deviations using a modular and extensible approach. Then, it relies on game theory to predict the behaviour of rational users. Finally, *RACOON* provides a simulator to rapidly assess the behaviour and performance of the system. Evaluation, performed using simulations and a real prototype with 100 users, shows that the configuration proposed by *RACOON* allows all users to visualise a quality stream even in presence of rational users.

Experiments presented in this paper were carried out using the Grid'5000 testbed, supported by a scientific interest group hosted by Inria and including CNRS, RENATER and several Universities as well as other organizations (see https://www.grid5000.fr).

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APPENDIX A
SPECIFICATION OF THE CASE STUDY

In the following, we present the XML Schema for the *RACOON* Specification Model. Figure 10 shows a diagram of the schema.

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    <xs:complexType>
     <xs:sequence>
      <xs:element name="property" maxOccurs="unbounded"
                  minOccurs="0">
       <xs:complexType>
        <xs:simpleContent>
         <xs:extension base="xs:float">
          <xs:attribute type="xs:string" name="name"
                  use="required"/>
         </xs:extension>
        </xs:simpleContent>
       </xs:complexType>
      </xs:element>
     </xs:sequence>
    </xs:complexType>
   </xs:element>
  </xs:sequence>
  <xs:attribute type="xs:string" name="name"/>
 </xs:complexType>
</xs:element>
</xs:schema>
```

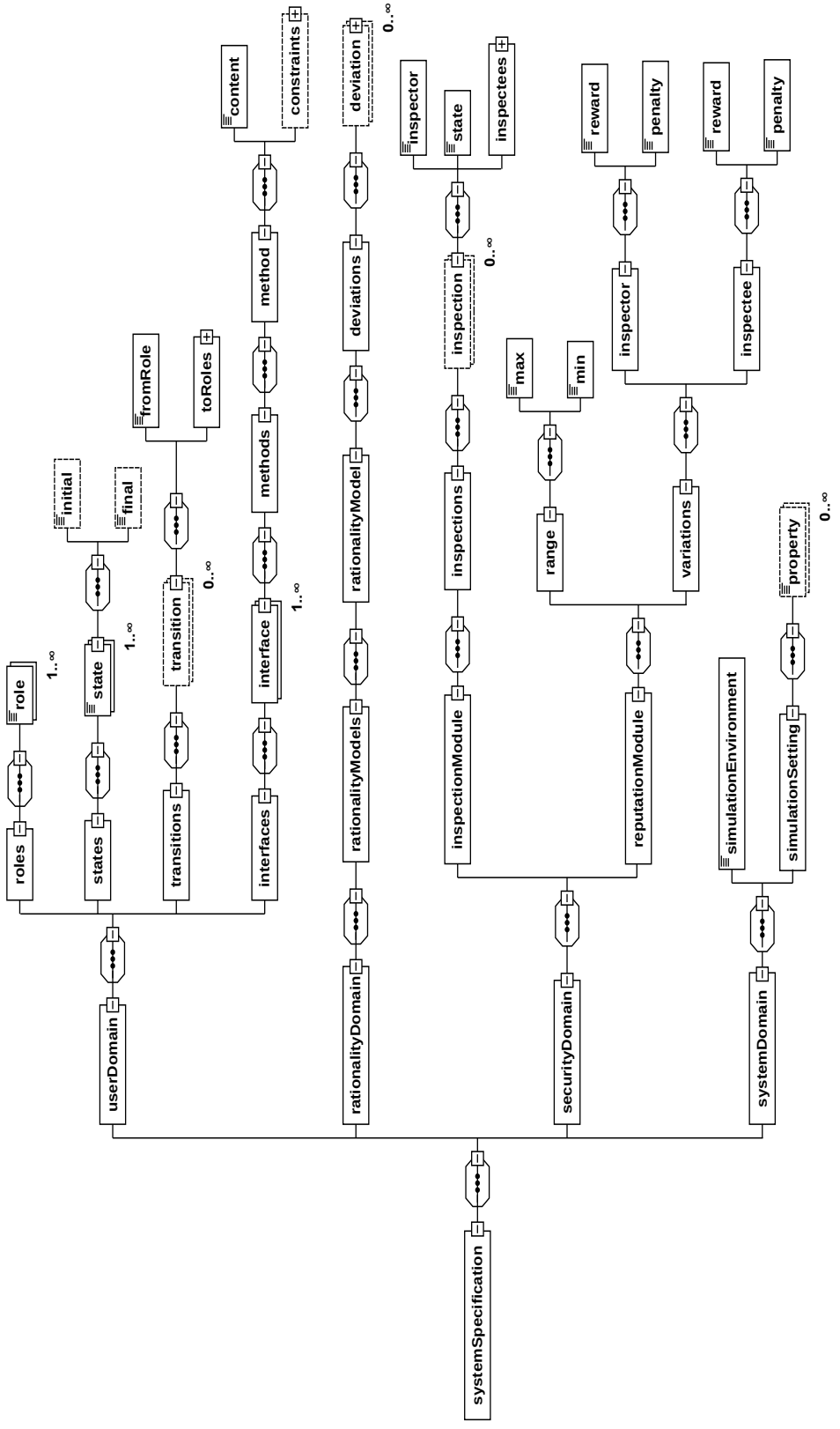

Fig. 10: The diagram of the XML Schema for the *RACOON* Specification Model.

APPENDIX B
SPECIFICATION OF THE CASE STUDY

In the following, we present the XML encoding of our case study specification.

```xml
<systemSpecification name="P2PliveStreaming">
<userDomain>
  <roles>
    <role name="sender" />
    <role name="receiver" />
  </roles>
  <states>
    <state name="s0"> <initial /> </state>
    <state name="s1" />
    <state name="s2" />
    <state name="s3"> <final /> </state>
  </states>
  <transitions>
    <transition name="t0" interface="i0"
                fromState="s0" toState="s1">
      <fromRole>sender</fromRole>
      <toRoles>
        <toRole>receiver</toRole>
      </toRoles>
    </transition>
    <transition name="t1" interface="i1"
                fromState="s1" toState="s2">
      <fromRole>receiver</fromRole>
      <toRoles>
        <toRole>sender</toRole>
      </toRoles>
    </transition>
    <transition name="t2" interface="i2"
                fromState="s2" toState="s3">
      <fromRole>sender</fromRole>
      <toRoles>
        <toRole>receiver</toRole>
      </toRoles>
    </transition>
  </transitions>
  <interfaces>
    <interface name="i0">
      <methods>
        <method name="propose">
          <content name="m0" type="list" />
        </method>
      </methods>
    </interface>
    <interface name="i1">
      <methods>
        <method name="request">
          <content name="m1" type="list" />
          <constraints>
            <constraint type="subset" wrtContent="m0" />
          </constraints>
        </method>
      </methods>
    </interface>
    <interface name="i2">
      <methods>
        <method name="serve">
          <content name="m2" type="list" />
          <constraints>
            <constraint type="equal" wrtContent="m1" />
          </constraints>
        </method>
      </methods>
    </interface>
  </interfaces>
</userDomain>
<rationalityDomain>
  <rationalityModels>
    <rationalityModel name="communication" enabled="true">
      <deviations>
        <deviation name="timeout">
          <roles>
            <role>sender</role>
          </roles>
        </deviation>
        <deviation name="subset">
          <roles>
            <role>sender</role>
            <role>receiver</role>
          </roles>
        </deviation>
        <deviation name="multicast">
          <roles> <role>sender</role> </roles>
        </deviation>
      </deviations>
    </rationalityModel>
  </rationalityModels>
</rationalityDomain>
<securityDomain>
  <inspectionModule>
    <inspections>
      <inspection probability="0.15">
        <inspector>sender</inspector>
        <state>s2</state>
        <inspectees>
          <inspectee>receiver</inspectee>
        </inspectees>
      </inspection>
      <inspection probability="0.1">
        <inspector>receiver</inspector>
        <state>s2</state>
        <inspectees>
          <inspectee>sender</inspectee>
        </inspectees>
      </inspection>
    </inspections>
  </inspectionModule>
  <reputationModule>
    <range>
      <max>10</max>
      <min>0</min>
    </range>
    <variations>
      <inspector>
        <reward type="fixed">1</reward>
        <penalty type="fixed">0</penalty>
      </inspector>
      <inspectee>
        <reward type="fixed">1</reward>
        <penalty type="invrep">8</penalty>
      </inspectee>
    </variations>
  </reputationModule>
</securityDomain>
<systemDomain>
  <simulationEnvironment name="p2pOverlayNetwork" />
  <simulationSetting>
    <property name="simulationRuns">1</property>
    <property name="networkSize">500</property>
    <property name="messageLoss">0</property>
    <property name="rationalProportion">0.5</property>
    <property name="mediaSize">100000</property>
    <property name="broadcastSize">25</property>
    <property name="broadcastAudience">0.05</property>
    <property name="playoutDelay">10</property>
    <property name="fanout">5</property>
    <property name="period">5</property>
    <property name="transmissionLimit">500</property>
  </simulationSetting>
</systemDomain>
</systemSpecification>
```

APPENDIX C
AUGMENTATION ALGORITHM

In the following, we present the algorithm to generate the three *Communication Rationality*'s deviations for reducing communication costs: *timeout*, *subset*, and *multicast* deviations. These deviations augment the original User domain representation of the protocol, and produce as output the *augmented protocol*.

Data: The data structure P parsed from the User domain specification

```
1  Algorithm CreateCommDeviations(P)
3      NFS := non-final states in P
5      foreach s ∈ NFS do
7          OT := set of the outgoing transitions of s
9          if OT has not legal timeout then
11             CreateTimeoutDeviation(s)
13         foreach transition t ∈ OT do
15             st := target state of t
17             M := set of methods in t.interface
19             if m ∈ M| m.content is a complex type then
21                 CreateSubsetDeviation(st, t, m)
23             if t.toRoles.size > 1 then
25                 CreateMulticastDeviation(st, t)
27     UpdateConnections(P)
28 Procedure CreateTimeoutDeviation(s)
30     illegalState := new final state
32     dev := new transition from s to illegalState
34     devIntf := new interface
36     devIntf.method := new method with name "timeout"
38     add illegalState, dev and devIntf to P
39 Procedure CreateSubsetDeviation(st,t,m)
41     illegalState := new state
43     dev := new transition from st to illegalState
45     copy t.fromUser and t.toUsers into dev
47     devMethod := m
49     devMethod.content := subset of m.content
51     devIntf := t.interface
53     replace m with devMethod into devIntf
55     add illegalState, dev and devIntf to P
56 Procedure CreateMulticastDeviation(st,t)
58     illegalState := new state
60     dev := new transition from st to illegalState
62     copy t.fromUser into dev
64     dev.toUsers := subset of t.toUsers
66     devIntf := t.interface
68     add illegalState, dev and devIntf to P
```

A. Timeout Deviations

The algorithm checks for each non-final state s of the protocol whether s has no outgoing transition that executes a legal timeout. If so, calls the procedure *CreateTimeoutDeviation*. This creates a new final state $illegalState$ and connects it with s by a timeout deviation (i.e., a new transition dev and the related interface $devIntf$).

B. Subset Deviations

The algorithm considers all the outgoing transition of each non-final state s. If a transition t in this set implements a method m that transmits a complex-type content, then calls the procedure *CreateSubsetDeviation*. The procedure creates a new state ($illegalState$), a new transition (dev) and a new interface ($devIntf$) to represent the deviation. The interface defines a method $devMethod$ that is a copy of m except for the content, which is a subset of the legit one ($m.content$).

C. Multicast Deviations

If an outgoing transition t of a non-final state s targets more than one recipient, then the algorithm launches the procedure *CreateMulticastDeviation*. A new state ($illegalState$) is then generated, and it is connected to s with a new transition dev. Such transition is equal to t but for the list of recipients, which is a subset of the one of t ($t.toUsers$).

D. UpdateConnections

The algorithm ends by calling the procedure *UpdateConnections*, which generates the transitions between the new illegal states and the other states of the automaton. For example, in Fig. 6, the transition between s_{0s} and s_2 is created by the *UpdateConnections* procedure.