TEMPEST - Synthesis Tool for Reactive Systems and Shields in Probabilistic Environments

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Abstract. We present Tempest, a synthesis tool to automatically create correct-by-construction reactive systems and shields from qualitative or quantitative specifications in probabilistic environments. A shield is a special type of reactive system used for run-time enforcement; i.e., a shield enforces a given qualitative or quantitative specification of a running system while interfering with its operation as little as possible. Shields that enforce a qualitative or quantitative specification are called safety-shields or optimal-shields, respectively. Safety-shields can be implemented as pre-shields or as post-shields, optimal-shields are implemented as post-shields. Pre-shields are placed before the system and restrict the choices of the system. Post-shields are implemented after the system and are able to overwrite the system’s output. Tempest is based on the probabilistic model checker Storm, adding model checking algorithms for stochastic games with safety and mean-payoff objectives. To the best of our knowledge, Tempest is the only synthesis tool able to solve 2¹/²-player games with mean-payoff objectives without restrictions on the state space. Furthermore, Tempest adds the functionality to synthesize safe and optimal strategies that implement reactive systems and shields.

1 Introduction

Reactive synthesis aims to automatically construct correct and efficient systems w.r.t. a formal specification and has been increasingly used in a wide range of safety-critical applications. A natural model for reactive synthesis is to model some inputs from the environment probabilistically and some adverserially. For adverserial inputs, the synthesized system assumes the worst case, for probabilistic inputs the average case. The corresponding synthesis problem is mapped to solving a competitive stochastic turn-based game, i.e., a 2¹/²-player game. Qualitative specifications specify the functional requirements of reactive systems. With a quantitative specification such as mean-payoff objectives, we can measure how well a system satisfies the specification.

Shield synthesis defines a synthesis framework to construct run-time enforcement modules called shields to guarantee the correctness of running systems.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 956123 - FOCETA.
The concept of shielding is very general. Shields that enforce qualitative objectives are so-called safety-shields [1]. For safety-shields, we distinguish between pre-shielding and post-shielding as depicted in Fig. 1. In pre-shielding the shield is implemented before the system and restricts the choices for the system to a list of correct actions. Pre-shielding is becoming increasingly important in the setting of safe reinforcement learning [9]. In post-shielding, the shield monitors the actions selected by the system and corrects them if the chosen action could lead to a specification violation. Shields that enforce quantitative measures are called optimal-shields [2] and are implemented as post-shields. Tempest is able to synthesize optimal-shields that enforce a mean-payoff objective. Optimal-shields that enforce multiple quantitative objectives can be obtained via a linear combination to give an approximate solution of a single mean-payoff objective. For instance, the decision whether an optimal-shield should interfere could be based on first, a performance objective to be minimized by the shield, and second, an interference cost for changing the output of the system. An optimal-shield can then be computed by minimizing a single mean-payoff objective obtained by combining both measures, thus guaranteeing maximal performance with minimal interference.

Tempest capabilities. The core functionality of Tempest is the synthesis of reactive systems and shields in environments that incorporate uncertainty. To the best of our knowledge, Tempest is the only tool able to solve 2/2-player games with mean-payoff objectives and qualitative objectives given in probabilistic temporal logics, without any restrictions on the state space. Furthermore, Tempest is designed as synthesis tool. Therefore, the computed strategies can intuitively be used as the synthesized system, which is not the case for many game-solving tools. Tempest is the first tool available for the synthesis of shields and is able to synthesize pre-safety and post-safety-shields, and optimal-shields.

Implementation and availability. The tool is written in C++ and builds upon the code-base of the model checker Storm [8], extending existing features to provide the capability of solving stochastic games. Tempest is available under the GPL-3 open source license. The tool and its source code, along with a docker image and several examples, are available from the Tempest web page.

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3 http://www.tempest-shielding.xyz
Connections to other tools. Probabilistic model checking tools like PRISM [10] and Storm [8] provide verification of quantitative reward-based properties and qualitative properties in probabilistic temporal logics. Many synthesis tools based on games are available and widely used, for example, UPPAAL-Tiga [3] is able to solve qualitative timed games, GIST [4] solves qualitative stochastic games, and QUASY [5] solves mean-payoff 2-player games. PRISM-games 3.0 [7] is able to solve turn-based stochastic multi-player games under a variety of properties including long-run average [6]. However, for solving long-run average objectives, PRISM-games needs the game to be a controllable multi-chain, i.e., one of the players needs to be able to reach every end-component from any state with probability one. This is a strong assumption on the structure of the game graph, which many models used in synthesis do not fulfill. In contrast, Tempest does not rely on any assumptions on the structure of the game graph.

Acknowledgements. We would like to thank both Tim Quatmann and Joost-Pieter Katoen for their continuous help on getting acquainted with the source code of Storm.

2 Model and Property Specification

Tempest Model Specification. Tempest supports turn-based stochastic multi-player games (SMGs) and uses PRISM-games’s modelling language to describe the game [7]. The players are divided in two competing coalitions, where the first team is working together to satisfy or maximize/minimize a property given in rPATL [6]. In each state, exactly one player chooses an available probabilistic transition to determine the next state. A strategy for a player determines the choices of transitions made by the player.

Tempest Property Specification. For the synthesis of reactive systems, Tempest uses the property specification language of PRISM-games to express properties in rPATL [6]. We give a few examples that can be used in Tempest:

- $\langle\langle 1, 2\rangle\rangle P_{max=r}[F \text{target}]:$ Using the operator $P_{max=r}$, Tempest computes a strategy for the player coalition of player 1 and 2 that guarantees to reach target with the largest probability.

- $\langle\langle 1, 2\rangle\rangle R_{max=r}[S]:$ Using the operators $R$ and $S$, Tempest synthesizes a strategy that maximizes the expected averaged reward $r$ in the long-run.

Synthesis of safety-shields. For the synthesis of shields, Tempest extends the property specification language. Let the safety-value of an action in a certain state be the maximal probability to stay safe within the next $k$ steps when executing this action. A safety-shield decides whether an action is blocked in a certain state based on either an absolute threshold $\gamma$, or a relative threshold $\lambda$. A shield using an absolute threshold blocks all actions with a safety-value smaller than $\gamma$. By using a relative threshold, actions are blocked with a safety-value smaller than the best safety-value of an action in the current state times $\lambda$. The syntax for safety-shielding requires to specify the type of shielding using the keywords PreSafety and PostSafety, and to define the used threshold. We give the following examples:
\[\langle\text{PreSafety, } \gamma = 0.9\rangle\langle\text{shield}\rangle P_{\max = 14} [G^{\leq 14} !\text{crash}]\] Using this property, Tempest synthesizes a pre-safety-shield that allows all actions that do not cause a crash with a maximal probability of 0.9 within the next 14 time steps.

\[\langle\text{PostSafety, } \lambda = 0.95\rangle\langle\text{shield}\rangle P_{\max = 14} [G^{\leq 14} !\text{crash}]\] Tempest synthesizes a post-safety-shield that blocks all actions using the relative threshold \(\lambda\).

**Synthesis of optimal-shields.** The property starts with the keyword `Optimal` followed by the expression used to compute the long run average. For example:

\[\langle\text{Optimal}\rangle\langle\text{shield}\rangle R_{\min = 3} [S]\] Tempest computes an optimal shield that guarantees the long-run average reward of \(r\).

### 3 Tempest Synthesis of Strategies

Tempest computes a memoryless deterministic strategy, implementing a reactive system or a shield, under which the specified property can be guaranteed. The strategy is computed using value iteration to solve the coalition game. Fig. 2 shows sample outputs of the strategies of the first experiment given in Section 4, implementing pre-safety and post-safety-shields. In the pre-shielding case, the strategy provides for any state a list of allowed actions with its corresponding safety-value. The strategy for post-shielding defines for every state and available action, the action to be forwarded by the shield.

**Pre-Safety-Shield with absolute comparison (gamma = 0.8):**

| State ID [Label]: 'Allowed Actions' [Value]: (<Action ID Label>) |
|---------------------------------------------------------------|
| 0 [move=0 & x1=0 & y1=0 & x2=4 & y2=4]: 1.0:0{e}; 1:0{s} |
| 3 [move=0 & x1=1 & y1=0 & x2=3 & y2=4]: 0.9:0{e}; 1:0{w} |
| 4 [move=0 & x1=1 & y1=0 & x2=4 & y2=4]: 0.9:0{e}; 1:0{w} |
| ....... |

**Post-Safety-Shield with relative comparison (lambda = 0.95):**

| State ID [Label]: 'Forwarded Actions' [Action ID Label]: <Forwarded Action ID Label> |
|-------------------------------------------------------------------------|
| 0 [move=0 & x1=0 & y1=0 & x2=4 & y2=4]: 0{e}:0{e}; 1{s}:1{s} |
| 3 [move=0 & x1=1 & y1=0 & x2=3 & y2=4]: 0{e}:2{w}; 1{s}:2{w} |
| 4 [move=0 & x1=1 & y1=0 & x2=4 & y2=4]: 1{s}:3{n}; 3{n}:3{n} |
| ....... |

Fig. 2: Synthesized strategies implementing a pre-safety-shield (top) and a post-safety-shield (bottom).

### 4 Tempest in Action

**High-Level Planning in Robotics.** A classical application of reactive synthesis is the domain of automated high-level planning in robotics. We consider a warehouse floor plan with several shelves, see Fig. 3 (left). To parametrize the experiment, we consider floor plans with \(n \times 3\) shelves with \(2 \leq n \leq 20\). A robot operates together among other robots within the warehouse. Tempest can be used in this setting to synthesize controllers for the robot that perform certain tasks, as well as shields used to ensure safe operation of the robot, or to guarantee
Controller synthesis: Using Tempest, we synthesize a controller for the robot that repeatedly picks up packages from one of the entrances and delivers them to the exits. We use the mean-payoff criterion to specify that the stochastic shortest paths should be taken. Safety-shield synthesis: A safety-shield can be synthesized to enforce collision avoidance with other robots. In the experiments, we used a finite horizon of 14 steps and a relative threshold of $\lambda = 0.9$. Optimal-shield synthesis: During operation, a corridor may be blocked. A robot should not unnecessarily wait for the corridor to be traversable when alternative paths exist. We synthesize an optimal-shield that penalizes ‘waiting’ and is able to enforce a detour when waiting gets too expensive.

Results. The models, parameters, and properties used for all experiments can be found on the Tempest website. The results for the synthesis-times are depicted in Fig. 3(right). The sizes of state space of the game graphs range from 5184 states for $n = 2$ to 186624 states for $n = 20$. The results for optimal-shields use the axis on the right hand-side. The times for creating pre-safety and post-safety-shields are identical. To compare our results, we tried to compute a strategy for the optimal controller in PRISM-games 3.0 which resulted in an error. By proper modelling, we were able to synthesize safe controllers comparable to the safety-shield using PRISM-games, resulting in better synthesis-times for Tempest.
Optimal-Shielding in Urban Traffic Control. Avni et al. [2] synthesize optimal-shields that overwrite the commands of a traffic-light controller modeled in the traffic simulator SUMO. The optimal-shield needs to balance the number of waiting cars per incoming road with the cost for interfering with the traffic light controller. The example is parametrised with the cut-off parameter $k$ that defines the maximal modelled number of waiting cars per road. The comparison of the synthesis-times from Avni et al.’s implementation and Tempest are shown in Fig. 4 (right), showing a difference by orders of magnitudes in favor of Tempest.

5 Conclusion and Future Work

We have introduced Tempest, a tool for the synthesis of reactive systems and shields with properties given in rPATL capturing qualitative and quantitative objectives with probabilities. Currently, Tempest supports perfect-information SMGs with full information. In future work, we will investigate in efficient techniques to deal with partial information. Furthermore, we will extend Tempest’s synthesis algorithm to support strategies with finite memory with deterministic and stochastic-updates.

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