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Models for large-scale systems

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SEVENTH FRAMEWORK PROGRAMME

Models for large-scale systems

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Abstract

This deliverable presents the results we obtained in the setting of games played on large-scale models. This report is split into two parts:

- the first part is about games with an arbitrary number of identical components. These models are especially relevant for collective adaptive systems, which are very often composed of a (possibly large) number of copies of identical components. We handle this multiplicity by using parametrized-verification techniques, with the aim of proving correctness of the global system for any (fixed) number of copies of the component.
- the second part focuses on games with partial observation. The basic setting of games for synthesis assumes that all players are able to fully observe the global state of the system. While this might be relevant for smaller systems, this is definitely unrealistic for large-scale systems. We obtained various results in different directions in the setting of games with partial observation, which we summarize in this second part.

The list of publications on page 14 lists the corresponding papers, which contain the full details. Remark that this deliverable mainly focuses on the *definition of models* for large-scale systems. Deliverable D2.3 (due date: month 36) will focus on *algorithms for games played on networks of systems*. So this deliverable will only briefly mention the algorithms that we have obtained in this direction.

Contents

Introduction

During the last 20 years, game theory has been successively used in the fields of formal verification and automated synthesis: game-based models are a well-suited formalism for representing the interactions between various components of a complex system, and efficient algorithms have been developed for computing winning strategies in such games, which in turn can be transformed into controllers that are correct by construction.

In order to deal with large systems however, the plain models of games on graphs are not always adequate: first, collective adaptive systems are most often made of several copies of the same components. While describing an explicit model involving a (large) number of components is always possible, the state-space explosion phenomenon makes synthesis intractable in practice in these cases. Moreover, the *exact number* of components is not always known in advance, and it would be much more interesting to get correctness results for *any number* of components. In the first part of this deliverable, we summarize several models that we have studied in this setting, which includes the definition and study of several kinds of *symmetric games* (i.e., games composed of several copies of a component), and the development of symmetry reduction for games.

A second aspect that games on graphs have to take into account when modeling large-scale systems is partial observaiton: each single component of a collective adaptive systems will usually not observe the whole system, but instead it will mainly see and interact with a few of its neighbours. Taking such partial observation of the system into account is also an important feature of games, which does not only apply to large-scale systems, but is definitely inavoidable for those systems. The second part of this deliverable focuses on several frameworks that we have studied in this direction.

1 Symmetric games

Background. Symmetric systems, with which we broadly mean systems presenting important regularities, appear in many applications, in particular in networks of communicating devices. Various techniques have been developed for model checking such systems, in particular approaches in which the number of components is a parameter, thus answering the question whether the system behaves correctly for any (large enough) number of components [ES96, CEJS98, AJ99, DLL+11].

We extended some of these approaches to the setting of games.

1.1 Symmetric Games with Partial Observation

We handle the special case of multi-player systems where all the interacting systems (but possibly a few of them) are identical. This encompasses many situations involving computerized systems over a network. We propose a convenient way of modelling such situations, and develop algorithms for synthesizing a single strategy that, when followed by all the players, leads to a global Nash equilibrium. To be meaningful, this requires symmetry assumptions on the arena of the game (the board should look the same to all the players). We also include imperfect observation of the other players,

[ES96] E. Allen Emerson and A. Prasad Sistla. Symmetry and model checking. *Formal Methods in System Design*, 9(1-2):105–131, August 1996.

[CEJS98] Edmund M. Clarke, E. Allen Emerson, Somesh Jha, and A. Prasad Sistla. Symmetry reductions in model checking. In Alan J. Hu and Moshe Y. Vardi, editors, *Proceedings of the 10th International Conference on Computer Aided Verification (CAV'98)*, volume 1427 of *Lecture Notes in Computer Science*, pages 147–158. Springer-Verlag, June-July 1998.

[AJ99] Parosh Aziz Abdulla and Bengt Jonsson. On the existence of network invariants for verifying parameterized systems. In Ernst Rüdiger Olderog and Bernhard Steffen, editors, *Correct System Design, Recent Insight and Advances*, volume 1710 of *Lecture Notes in Computer Science*, pages 180–197. Springer-Verlag, 1999.

[DLL+11] Alexandre David, Kim Gulstrand Larsen, Axel Legay, Marius Mikučionis, Danny Bøgsted Poulsen, Jonas van Vliet, and Zheng Wang. Statistical model checking for networks of priced timed automata. In Uli Fahrenberg and Stavros Tripakis, editors, *Proceedings of the 9th International Conferences on Formal Modelling and Analysis of Timed Systems, (FORMATS'11)*, volume 6919 of *Lecture Notes in Computer Science*, pages 80–96. Springer-Verlag, September 2011.

which we believe is relevant in such a setting.

We propose a convenient model for representing large interacting systems, which we call game structure. A game structure is made of multiple copies of a single arena (one copy per player); each player plays on his own copy of the arena. As mentioned earlier, the players have imperfect information about the global state of the game (they may have a perfect view on some of their "neighbours", but may be blind to some other players). In symmetric game structures, we additionally require that any two players are in similar situations: for every pair of players (A, B), we are able to map each player C to a corresponding player D with the informal meaning that 'player D is to B what player C is to A'. Of course, winning conditions and imperfect information should respect that symmetry.

Formally, an *n-player game network* is a tuple $\mathcal{G} = \langle G, (\equiv_i)_{i\in[n]}, (\Omega_i)_{i\in[n]}\rangle$ s.t.

- $G = \langle \mathsf{States}, \{A\}, \mathsf{Act}, \mathsf{Mov}, \mathsf{Tab}\rangle$ is a one-player arena;
- for each $i \in [n]$, $\equiv_i$ is an equivalence relation on States^n (extended in a natural way to sequences of states of States^n). Two $\equiv_i$-equivalent configurations are indistinguishable to player i. This models *imperfect information* for player i;
- for each $i \in [n]$, $\Omega_i \subseteq (\mathsf{States}^n)^\omega$ is the objective of player i. We require that for all $\rho, \rho' \in (\mathsf{States}^n)^\omega$, if $\rho \equiv_i \rho'$ then ρ and ρ' are equivalently in Ω_i.

The semantics of this game is defined as the "product game" $\mathcal{G}' = \langle \mathsf{States}', [n], \mathsf{Act}, \mathsf{Mov}', \mathsf{Tab}', (\Omega_i)_{i\in[n]}\rangle$ where $\mathsf{States}' = \mathsf{States}^n$, $\mathsf{Mov}'((s_0, \ldots, s_{n-1}), i) = \mathsf{Mov}(s_i)$, and the transition table is defined as

$$\mathsf{Tab}'((s_0, \ldots, s_{n-1}), (m_i)_{i\in[n]}) = (\mathsf{Tab}(s_0, m_0), \ldots, \mathsf{Tab}(s_{n-1}, m_{n-1})).$$

If we impose no restriction on the observation relation, n-player game networks do not fully capture symmetries in a system. Besides playing on similar arenas, we add the extra requirement that all the players are in similar situations w.r.t. the other players. To capture the symmetries in a system, we first assume that the network of players has a symmetric architecture, and in particular that all players have the same point-of-view on the behaviour of the system. We therefore assume that each player has the same number of players that he can really distinguish (we call them his *neighbours*), and that he cannot distinguish the players outside this neighbourhood. An acceptable behaviour in this system then has to respect the symmetry induced by this undistinguishability.

Given a permutation π of $[n]$, for a configuration $t = (s_i)_{i\in[n]}$ we define $t(\pi) = (s_{\pi(i)})_{i\in[n]}$; similarly, for a path $\rho = (t_j)_{j\in\mathbb{N}}$, we define $\rho(\pi) = (t_j(\pi))_{j\in\mathbb{N}}$.

A game network $\mathcal{G} = \langle G, (\equiv_i)_{i\in[n]}, (\Omega_i)_{i\in[n]}\rangle$ is then said *symmetric* whenever for any two players $i, j \in [n]$, there is a permutation $\pi_{i,j}$ of $[n]$ such that $\pi_{i,j}(i) = j$ and satisfying the following conditions: for every $i, j, k \in [n]$,

1. $\pi_{i,i}$ is the identity, and $\pi_{k,j} \circ \pi_{i,k} = \pi_{i,j}$; hence $\pi_{i,j}^{-1} = \pi_{j,i}$.
2. the observation made by the players is compatible with the symmetry of the game:
3. objectives are compatible with the symmetry of the game: for every play ρ, $\rho \in \Omega_i$ iff $\rho(\pi_{i,j}^{-1}) \in \Omega_j$.

The mappings $\pi_{i,j}$ define the symmetry of the game: $\pi_{i,j}(k) = l$ means that player l plays vis-à-vis player j the role that player k plays vis-à-vis player i.

Example 1 *Extending the previous example, consider a ring of n devices, where each device has perfect information about their left and right neighbours. This is symmetric, with for instance the following symmetric representation: $\pi_{i,j}(i + k) = j + k \mod n$. The devices could also have more information, for instance the Parikh image of all the nodes in the ring (i.e., for each state of the arena, how many devices in the ring are in that state).*

Example 2 *Consider a card game tournament with six players, three on each table. Here each player has a left neighbour, a right neighbour, and three opponents at a different table. To model this, one could assume player 0 knows everything about himself, and has some informations about his right neighbour (player 1) and his left neighbour (player 2). But he knows nothing about players 3, 4 and 5.*

Now, the role of player 2 vis-à-vis player 1 is that of player 1 vis-à-vis player 0 (he is his right neighbour). Hence, we can define the symmetry as

$\pi_{0,1}(0) = 1$, $\pi_{0,1}(1) = 2$, $\pi_{0,1}(2) = 0$, *and* $\pi_{0,1}(\{3,4,5\}) = \{3,4,5\}$ *(any choice is fine here). As an example, the observation relation in this setting could be that player* 0 *has perfect knowledge of his set of cards, but only knows the number of cards of players* 1 *and* 2*, and has no information about the other three players. Notice that other observation relations would have been possible (for instance, giving more information about the right player).*

We obtained several undecidability results, in particular that the parameterized synthesis problem (aiming to obtain one policy that forms a Nash equilibrium when applied to any number of participants) is undecidable. We then characterized the complexity of computing (constrained) pure symmetric Nash equilibria in symmetric game structures, when objectives are given as LTL formulas, and when restricting to memoryless and bounded-memory strategies. We also proved that dropping the memory bound leads to undecidability.

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References: [BMV14]

1.2 Networks of communicating systems

The approach developed in the previous section very quickly leads to undecidability. There are several reasons for that, among which partial observation and the use of deterministic and memoryful strategies.

We recently started working on a conceptually simpler model in which a parametric number of components run independently, but may communicate via a shared variable. The pace by which the systems evolve is given by a randomized scheduler. Formally, such a network is given by a finite-state automaton $\mathcal{A}$ whose transitions are labelled with either $w(d)$ or $r(d)$, for d ranging in a finite set $\mathcal{D}$; the first labeling corresponds to writing d in the shared memory, while $r(d)$ may only be taken if the shared memory contains d.

Example 3 *Figure 1 displays such an example. Consider an arbitrary num-*

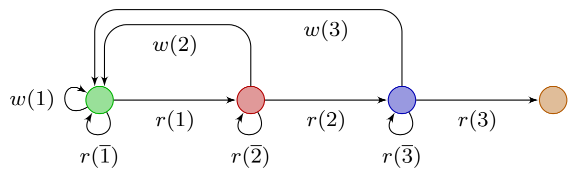

Figure 1: Example of a process

ber of such processes running concurrently, starting from the leftmost state and value 0 *written in the shared memory, with a randomized scheduler activating some available transition of one of the processes at each step. Eventually, one of the processes will write* 1 *in the shared memory, which will make the transition* $r(1)$ *available. One or several processes will move to the second state. At least two of them are needed in that state in order to be able to trigger the transition to the third state (one for writing* 2 *and one for reading this value), where again two processes are needed to reach the last state. Since "bad" transitions go back to the initial state, the probability that one processes reaches the last state is* 1*, provided that there are at least three processes running in parallel.*

We are currently working on solving this problem, trying to find an algorithm for deciding if the final state is reachable with probability 1. Our aim is then to move to the game setting, where from a non-deterministic model, we will want to find a strategy which, when applied to all the processes, will make the final state reachable with probability 1.

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2 Games with partial observation

Background. Partial observation is a must-have in models for large-scale systems. The models described in the previous part all have a flavour of partial observation. However, it is important to consider partial observation alone, without the parameterized setting, as it already makes the verification algorithms much more complex.

Many different notions of partial observation can be thought of. We studied several of them, for which we report our results below.

2.1 Model checking $\mathbf{ATL}_{sc}$ on models with partial-observation

Partial observation already occured in a weak sense in our recent works on ATL with strategy contexts [LM15]: indeed, we assume in this setting that the players are not able to observe the actions played by the other players, but only the states visited during the play. In other terms, strategies only depend on the sequence of visited states, rather than on the sequence of move vectors proposed by the players.

In a recent work [LMS15], we tried to include even more partial observation, using the classical approach: the state space is partitionned into groups of states that cannot be distinguished by the players. More formally, our game structures are augmented with equivalence relations $(\sim_a)_{a\in\mathsf{Agt}}$ over the states of the game structure. The relation $\sim_a$ indicates which states are observationaly-equivalent for player a: the strategy of player a then has to return the same action from two equivalent states (or after two sequences of pairwise equivalent states).

Negative results already exist in this context: model checking ATL (already without strategy contexts) is undecidable, as was announced in [AHK02] and formally proved in [DŢ11]. Hence there is no hope of getting anything better in this setting.

We further restricted the setting to *uniform* partial observation, in which all players share the same equivalence relation. This can be used to model settings in which the players are not able to see the internal state of the central controller, for instance. We proved that under this restriction, we re-

[LM15] François Laroussinie and Nicolas Markey. Augmenting ATL with strategy contexts. *Information and Computation*, 2015. To appear.

[AHK02] Rajeev Alur, Thomas A. Henzinger, and Orna Kupferman. Alternating-time temporal logic. *Journal of the ACM*, 49(5):672–713, September 2002.

[DŢ11] Cătălin Dima and Ferucio Laurenţiu Ţiplea. Model-checking ATL under imperfect information and perfect recall semantics is undecidable. Research Report 1102.4225, arXiv, February 2011.

cover decidability of the model checking problem for ATL with strategy contexts. This required adapting the translation from ATL with strategy contexts into QCTL so that it is evaluated on the (complete) graph of observations, instead of on the graph underlying the game structure.

We are now trying to extend this approach to games with hierarchical informations, which is a classical setting where decidability can be recovered in distributed synthesis.

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References: [LMS15]

2.2 Information structure in interactive systems.

The first challenge, when dealing with multi-component systems, is posed by the size of the global configuration space that arises a the product of local configurations. One standard approach to this state-explosion problem relies on succinct, compositional representations. Typically, it is possible to recover the *control* structure of the global system effectively from component models. However, this is no longer true for the *information* structure that unfolds with the interaction between components in the presence of uncertainty. In [BV15a], we investigate imperfect-information games with regard to the question of how much memory is needed to decide on one control step following a history of imperfect observations. We show that, even for a very basic setting of two-player safety games with no communication abilities, the entire history of observations needs to be stored and that the full power of linear-space bounded automata is needed to decide on the action to take.

Imperfect, or partial, observation is an inherent feature of systems with multiple components. In large systems, it is realistic to assume that each component has only partial access to information on the internal state of every other component. Moreover, even when the relevant information is accessible, it may be observed only with a certain time lag.

Accordingly, the main focus of our research was on establishing design principles for multi-component systems with partial observation in order to guarantee that the information structure is bounded and can be analysed effectively.

Participants: Dietmar Berwanger (CNRS)
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References: [BV15a]

2.3 Information-centered modelling.

Our approach is based on an explicit modelling of the information flow in multi-component systems. In contrast to the traditional agent-centred representation, we developed an information-centred perspective.

One concrete instance of this approach consists in the decomposition of games into knowledge gaps, presented in [BM14]. The solution relies on the identification of synchronisation barriers where the multiple players of a game attain common knowledge of the global control state. Whenever such a barrier is reached, the history of interaction can be reset. This allows to analyse infinite games as a finite collection of finite game instances. Our decomposition procedure is of low complexity (NLOGSPACE-complete), and the overall solution avoids the nonelementary complexity encountered by the classical agent-centered approach in the favourable case of hierarchical information [KV01].

Another strand of research concerned relaxations of the standard requirement of hierarchical information viewed as a necessary condition for decidabilty [APR01]. In [BMV15], we propose two extensions to the hierarchical information pattern, one that allows dynamic changes in the hierarchy order, and a second one that admits transient perturbations of the hierarchy condition. The former extension opens the way to applying multi-level synthesis procedures that allow to integrate abstraction methods. This is crucial to dealing with large state spaces.

[KV01] Orna Kupferman and Moshe Y. Vardi. Synthesizing distributed systems. In *Proceedings of the 16th Annual Symposium on Logic in Computer Science (LICS'01)*, pages 389–398. IEEE Comp. Soc. Press, June 2001.

[APR01] Salman Azhar, Gary Peterson, and John Reif. Lower bounds for multiplayer non-cooperative games of incomplete information. *Journal of Computers and Mathematics with Applications*, 11:957–992, 2001.

Participants: Dietmar Berwanger (CNRS)
Anup Basil Mathew (CNRS & CMI, India)
Marie Van Den Bogaard (CNRS)
References: [BM14], [BMV15]

2.4 Neutralisation of information-flow perturbations.

Our investigations on multi-component systems in the distributed setting gave rise to the intuition that algorithmic methods for games with perfect information may be adapted to deal with imperfect information resulting from limited perturbations of the information flow. As a concrete application, we investigate equilibria in games with delayed monitoring, where the information about the actions of players can only be observed after a bounded time lag [BV15b]. Our study shows that the effect of such lags can be neutralised by using delayed-response strategies.

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References: [BV15b]

2.5 Multi-player games with a weak adversary

For distributed synthesis, multi-player partial-observation games are considered with a set of partial-observation existential players (modeling the distributed system), against a perfect-observation universal player (modeling the adversarial environment). The problem of deciding if the existential players can ensure a reachability (or a safety) objective is undecidable in general, even for two existential players [PR89]. However, if the information of the existential players form a chain (i.e., existential player 1 more informed than existential player 2, existential player 2 more informed than existential player 3, and so on), then the problem is decidable [PR89].

One aspect of multi-player games that has been largely ignored is the presence of weaker universal players that do not have perfect observation.

[PR89] A. Pnueli and R. Rosner. On the synthesis of a reactive module. In *Proc. of POPL*, pages 179–190. ACM Press, 1989.

However, it is natural in the analysis of composite reactive systems that some universal players represent components that do not have access to all variables of the system. We considered multi-player games where adversarial players have partial observation, and obtained decidability results for 3-player games when the first player is existential and less informed than the second player who is universal (and for arbitrary information of the third player who is existential), which can be extended to an arbitrary number of players as long as the information of the first players forms a chain. We considered the symmetric case when the first player is more informed than the second player, and show that even when the first player has perfect observation there is a non-elementary lower bound on the memory required by winning strategies. This result is also in sharp contrast with distributed games, where if only one player has partial observation then the upper bound on memory of winning strategies is exponential.

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Laurent Doyen (CNRS)
References: [CD14]

2.6 Synthesis from reusable components

The synthesis of systems from existing reusable components is an active research direction, with several important lines of research, such as component-based construction [Sif05] and interface-based design [dAH01].

We consider a model of probabilistic components modeled as transducers with a probabilistic transition function, that corresponds to modeling systems where there is probabilistic uncertainty about the effect of input actions. Probabilistic uncertainty is also a convenient way to model the joint average behaviour of a large set of players. The synthesis problem then asks to assemble instances of the available components to construct a reactive system that satisfies a specification with the largest probability. In

[Sif05] J. Sifakis. A framework for component-based construction (Extended Abstract). In *SFEM'05*, pages 293–300, 2005.

[dAH01] Luca de Alfaro and Thomas A. Henzinger. Interface automata. In *Proceedings of the 9th Annual Symposium on Foundations of Software Engineering (FSE'01)*, pages 109–120. ACM Press, September 2001.

the usual case where the specification needs to be satisfied with probability 1, a solution to this problem would allow to construct a reliable systems from unreliable components.

We obtained several complexity and decidability results for this problem, by reductions to partial-observation games. We considered specifications defined as a parity conditions, which are a well-known canonical form to express all ω-regular specifications. When the parity condition is given by a separate monitor automaton, we show that the general synthesis problem of maximizing the probability to satisfy the specification is undecidable, while the interesting case of probability-1 synthesis is EXPTIME-complete. When the parity condition is embedded in the component definition, our reductions lead to games of perfect information (though the most natural interpretation of the problem is as a partial-observation game), and complexity NP $\cap$ coNP for the general synthesis problem. Such a low complexity is surprising for a synthesis problem, and it should be noted that the case of a separate monitor automaton is more realistic in practice.

Participants:	Krishnendu Chatterjee (IST Austria)
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	Moshe Vardi (Rice University, USA)
References:	[CDV15]

3 Conclusions and perspectives

Besides the substantial amount of results presented in this deliverable, several directions are currently being explored by the Cassting teams. In particular, we are developing algorithms for networks of systems, which will be the subject of a forthcoming deliverable. We are also continuing to explore various flavours of partial-observation games and distributed-synthesis settings, with the aim of getting more expressive models for which synthesis is tractable.

4 List of publications

[BM14] Dietmar Berwanger and Anup Basil Mathew. Infinite games with finite knowledge gaps. Research report 1411.5820, arXiv, 2014.

[BMV14] Patricia Bouyer, Nicolas Markey, and Steen Vester. Nash equilibria in symmetric games with partial observation. In Fabio Mogavero and Aniello Murano, editors, *Proceedings of the 2nd International Workshop on Strategic Reasoning (SR'14)*, volume 146 of *Electronic Proceedings in Theoretical Computer Science*, pages 49–55, Grenoble, France, April 2014.

[BMV15] Dietmar Berwanger, Anup Basil Mathew, and Marie Van den Bogaard. Hierarchical information patterns and distributed strategy synthesis. In Bernd Finkbeiner, Geguang Pu, and Lijun Zhang, editors, *Proceedings of the 13th International Symposium on Automated Technology for Verification and Analysis (ATVA'15)*, Lecture Notes in Computer Science, Shanghai, China, October 2015. Springer. To appear.

[BV15a] Dietmar Berwanger and Marie Van den Bogaard. Consensus game acceptors. In Igor Potapov, editor, *Proceedings of the 19th International Conference on Developments in Language Theory (DLT'15)*, volume 9168 of *Lecture Notes in Computer Science*, pages 108–119, Liverpool, UK, July 2015. Springer.

[BV15b] Dietmar Berwanger and Marie Van den Bogaard. Games with delays. a Frankenstein approach. In Prahladh Harsha and G. Ramalingam, editors, *Proceedings of the 35th Conference on Foundations of Software Technology and Theoretical Computer Science (FSTTCS'15)*, Leibniz International Proceedings in Informatics, Bangalore, India, December 2015. Leibniz-Zentrum für Informatik. To appear.

[CD14] Krishnendu Chatterjee and Laurent Doyen. Games with a weak adversary. In Javier Esparza, Pierre Fraigniaud, and Elias Koutsoupias, editors, *Proceedings of the 41st International Colloquium on Automata, Languages and Programming (ICALP'14) – Part II*, volume 8573 of *Lecture Notes in Computer Science*, pages 110–121, Copenhagen, Denmark, July 2014. Springer.

[CDV15] Krishnendu Chatterjee, Laurent Doyen, and Moshe Vardi. The complexity of synthesis from probabilistic components. In Magnús M. Halldórsson, Kazuo Iwama, Naoki Kobayashi, and Bettina Speckmann, editors, *Proceedings of the 42nd International Colloquium on Automata, Languages and Programming (ICALP'15) – Part II*, volume 9135 of *Lecture Notes in Computer Science*, pages 108–120, Kyoto, Japan, July 2015. Springer.

[LMS15] François Laroussinie, Nicolas Markey, and Arnaud Sangnier. $\mathsf{ATL}_{\mathsf{sc}}$ with partial observation. In Javier Esparza and Enrico Tronci, editors, *Proceedings of the 6th International Symposium on Games, Automata, Logics, and Formal Verification (GandALF'15)*, volume 193 of *Electronic Proceedings in Theoretical Computer Science*, pages 43–57, Genova, Italy, September 2015.