A Compositional Approach for Reliable Adaptation of Track-based Traffic Control Systems at Runtime

Maryam Bagheri, Marjan Sirjani, Ehsan Khamespanah, and Ali Movaghar

Abstract—In this paper, we propose a compositional approach for verifying autonomous track-based traffic control systems at runtime. This approach traces a sequence of changes propagated through the system and verifies the system concerning the changed/adapted components. The system is modeled by multiple interactive coordinated actor models, where each coordinated actor model corresponds to a component of the system. Each component interacts with several components, called its environment components. We define the operational semantics of a coordinated actor model and the multiple interactive coordinated actor models based on Timed Input Output Transition System (TIOTS). We call two (or more) TIOTSs composable if they do not reach an error state in their parallel composition. By detecting a change in a component, the component is adapted. If TIOTSs of the adapted component and its environment components are composable, the change does not propagate to the environment components and correctness constraints of the system are preserved. Otherwise, the change is propagated. In this case, all components affected by the change are adapted and are composed to form a composite component. It is then checked whether TIOTSs of the composite component and its environment components are composable. This procedure continues until the change does not propagate. To reduce the state space, for checking the composability we use a reduced version of the TIOTSs of the environment components. We implement our approach in the Ptolemy II framework. The results of our experiments indicate that the proposed approach improves the model checking time and the memory consumption.

Index Terms—Self-adaptive Systems, Model@Runtime, Compositional Verification, Track-based Traffic Control Systems, Ptolemy II

1 INTRODUCTION

A UTONOMOUS response to context changes is a distinguishing feature of self-adaptive systems, where a system is able to adjust its structure and behavior in response to changes in its environment and the system itself. Following a change, a sequence of changes may happen. In other words, to satisfy expected properties of a system, the system is adapted, while the adaptation may result in further changes in the system. For each change and its consequent adaptation, verifying the safety and quality properties of the system is necessary. Due to uncertainties in the context of a self-adaptive system, its reliability should be checked during its execution. Towards this aim, verification at runtime is recommended, where an abstract model of the system and its environment is designed as the model@runtime, is updated, and is verified during the system execution. The analysis results are used to develop an adaptation plan and the plan is issued to the system.

Verification at runtime due to its nature to be performed at runtime has strict time and memory constraints. Although there are approaches for verifying self-adaptive systems at runtime [1], [2], [3], [4], [5], [6], a few of them cope with these constraints and none of them study the change propagation phenomenon, where following a change in the context of a system, a sequence of changes may happen in the system. To deal with the time and memory constraints in checking a system at runtime, we propose an approach based on compositional verification [7], [8], where satisfaction of a global property over the whole system is deduced from satisfaction of local properties over components of the system. Our approach by detecting a propagation of the change through the system, dynamically extends its verifying domain to check the changed components.

Using the approach of this paper, the model of a system is decomposed into a set of components, while the behaviors of these components is presented by Timed Input Output Transition Systems (TIOTSs) [9]. This way, the expected behavior of the system is demonstrated by parallel composition of TIOTSs corresponding to the components. We call two (or more) TIOTSs composable if they do not reach an error state in their parallel composition. The composition reaches an error state if one of TIOTSs cannot progress the time, cannot receive an input, or cannot send an output.

Upon encountering a change, the affected component is adapted to the change. Each component of the model interacts with a set of components called its environment components. If TIOTSs of the adapted component and its environment components are composable, it means that the adaptation contains the change and prevents the possible effects of the change to be propagated to other components. In this case, the component has been adapted in a way that the correctness constraints of the system are satisfied. In contrast, the adaption may result in some disturbances in the environment components. In this case, TIOTSs of the
adapted component and its environment components are not composable and the change is propagated. To eliminate the effects of the change propagation, more adaptations by the environment components are needed. Now, the affected component and its adapted environment components are composed to form a composite component. Similarly, if TIOTSs of the composite component and its environment components are composable, it shows that the set of adaptations successfully contains the change, and the correctness constraints of the system are satisfied. Otherwise, the change is propagated to more components. The environment components of a composite component include the environment components of its constituent components and does not include the constituent components themselves.

Our approach is particularly proposed for autonomous Track-based Traffic Control Systems (TTCSs). TTCSs are large-scale, cyber-physical, safety and time critical systems in which the change propagation phenomenon is clearly visible as described in Section 2. In TTCSs, traffic passes through pre-specified tracks that based on the safe distance between the moving objects are divided into a set of sub-tracks. The sub-tracks are critical sections, accommodating only one moving object in-transit. A TTCS has a set of correctness constraints, i.e., the moving objects have to arrive at their destinations at the pre-specified times, the fuel of the moving objects should not be less than a threshold, the conflict in the system should be avoided, and the system should be deadlock-free. The controller in a TTCS coordinates the moving objects by safely rerouting/rescheduling them whenever a change happens to the environment of the system. It is necessary to ensure that the correctness constraints of a TTCS are preserved while it adapts itself to a sequence of changes propagated through the system.

In [10], we introduced a coordinated actor model to build the model runtime of a self-adaptive TTCS. In the coordinated actor model of a TTCS, each sub-track is modeled by an actor, the moving objects are considered as messages passed by the actors, and the controller is modeled by a coordinator, explained in Section 3. Since a TTCS is a large-scale system, it is divided into several control areas, and each area has its own controller. To model large-scale TTCSs, we proposed a two-layered model for multiple interactive coordinated actor models [11] consisting of a coordinated actor model per each area. The collaboration between the models is achieved through their coordinators and message passing among the actors.

Compositional verification is more effectively applicable to the multiple interactive coordinated actor models, since each component as a coordinated actor model interacts with its environment based on predefined interfaces. Each component should guarantee to be able to receive messages from its environment components and to send messages to its environment components at the pre-specified times. To exploit our approach for verifying self-adaptive TTCSs, we give the operational semantics of a coordinated actor model and the multiple interactive coordinated actor models based on TIOTSs, described in Section 4. We also define the parallel composition of two TIOTSs and explain when their composition reaches an error state. To detect the change propagation, we check whether TIOTSs of the adapted component and its environment components are composable, described in Section 5. To reduce the state space, TIOTSs of the environment components are reduced, since only the transitions related to sending messages from the environment to the component and vice versa are important. It is notable that our approach is inspired by the work of Clarke et al. [8], where each component of the model is supplied with a correctness property. In [8], by composing a component with an abstraction of its environment components and verifying a property over the composition, the satisfaction of the property over the whole system is proved. In contrast to [8], the correctness constraints in our approach are built into the model, and there is no need to express them with a logical formula.

To illustrate the applicability of our approach, we implement it in Ptolemy II [12]. Ptolemy II is an actor-oriented open source modeling and simulation framework. A Ptolemy model consists of actors that communicate via message passing. The semantics of communications of the actors in Ptolemy is defined by Models of Computation (MoCs), implemented in a set of predefined director components. In [11], we developed a Ptolemy template to model and analyze self-adaptive TTCSs. Our analysis in [11] was based on simulation, since Ptolemy II with its deterministic MoCs does not support model checking of a system. To provide assertion-based model checking for TTCSs in Ptolemy II, we develop a new director in this paper. Our director generates the state space of the affected component, automatically extends its verifying domain to include several components, and performs the reachability analysis. The results of our experiments for an example in the domain of Air Traffic Control system (ATC) indicate a significant improvement in the time and memory consumptions, described in Section 6.

In [13], we introduced the notion of a Magnifier for runtime compositional verification of self-adaptive TTCSs as a work in progress. This paper extends the work of [13] by developing the theoretical part of the Magnifier based on TIOTSs, and implement it in the Ptolemy II framework. We describe the related work in Section 2 and conclude the paper in Section 8. To the best of our knowledge, there have been no studies to verify TTCSs at runtime, while they adapt themselves to a change in their context. This paper is the first attempt that uses the idea of the compositional verification to not only track a change propagated through a TTCS, but also verify the system at runtime. Our approach also gives the idea of containing the change in the smallest area of the traveling space by selecting an adaptation policy (rerouting algorithm) that adheres to the timing constraints of the system.

2 Problem Definition

An ATC is a system equipped with supervision instruments that monitor and control flights along the airspace routes. ATC in the North Atlantic follows a track-based structure that is called an Organized Track System (OTS) [14]. The North Atlantic OTS consists of a set of nearly parallel tracks positioned in light of the prevailing winds to suit the traffic between Europe and North America. Based on the safe distance between two aircraft, the tracks are divided into a set
of sub-tracks. Each sub-track is a critical section that accommodates only one aircraft in-transit. ATC uses this structure to guarantee the safety and improve the performance. In the real world, each aircraft has an initial flight plan. An aircraft flight plan consists of its flight route as a sequence of the sub-tracks flown by the aircraft from its source airport to its destination, initial fuel, and time schedule decisions. The aircraft time schedule decisions consist of its departure time from its source airport, assumed arrival time at each sub-track in its route, and assumed arrival time at the destination airport. The initial flight plans are generated prior to takeoff, but dynamic changes in the weather conditions, delay in landing and taxiing, etc., may require some modifications in the aircraft flight plans. In other words, following a change in the airspace, a sequence of changes might happen. For instance, the aircraft flight plans are changed if a storm happens in a part of their flight routes. While changing aircraft flight plans, several safety issues should be considered; i.e. loss of the separation between two aircraft should be avoided, and the remaining fuel should be checked. To avoid conflicts, changing the flight plan of an aircraft may result in changing the flight plans of the other aircraft. These changes can be propagated to the whole system. Besides the safety concerns, performance metrics such as arrival times of the aircraft at their destinations or sub-tracks in their routes are important. In ATC, the controller is in charge of coordinating the aircraft by routing or rerouting them.

An example of the change propagation in an ATC system is described as follows. Assume Fig. 1(a) and Fig. 1(b) show a part of an ATC example with 18 sub-tracks (two areas). The traffic flows from the west to the east and vice versa. Each moving object of the eastbound traffic is able to travel towards a sub-track in the north, south, and east. The red sub-track is an unavailable sub-track through which no moving object can travel. For instance, if a storm happens in a part of the airspace, the aircraft cannot cross over the sub-tracks affected by the storm and are rerouted. The initial routes of the moving objects are shown in Fig. 1(a). The moving object with an unavailable sub-track in its route is rerouted and its new route is shown in Fig. 1(b). Suppose that the traveling times of the moving objects through each sub-track are the same and are equal to one. The initial flight routes and time schedule decisions of the purple and blue aircraft in Fig. 1(a) are \{7, 8, 9, 10, 11, 12, 6\} \{0, 1, 2, 3, 4, 5, 6\} and \{17, 11, 5, 4, 3\} \{5, 6, 7, 8, 9\}, respectively. For instance, the purple aircraft arrives at sub-track 7 at time zero and exits it at time one which is equal to its arrival time at sub-track 8. By the occurrence of a storm in sub-track 8, the route and time schedule of the purple aircraft are changed to \{7, 1, 2, 3, 9, 10, 11, 12, 6\} \{0, 1, 2, 3, 4, 5, 6, 7, 8\}, shown in Fig. 1(b). Thus, the purple aircraft arrives at sub-track 11 at time 6. At this time, the blue aircraft has to enter into sub-track 11 based on its initial flight route. To prevent the collision between two aircraft, the controller employs a rerouting algorithm (adaptation policy) and changes the route and time schedule of the blue aircraft to \{17, 16, 15, 9, 3\} \{5, 6, 7, 8, 9\}. As can be seen, by the occurrence of a change, e.g. a storm, a sequence of changes happens, e.g. rerouting a set of aircraft.

The track-based structure of ATC is followed in many applications, i.e. the rail traffic control systems, maritime transportation, smart hubs, unmanned vehicles, and centralized robotic systems with a mesh structure. In these systems, to reduce the risk of collision between the moving objects, the traveling space is divided into smaller safe regions, and a centralized controller manages the traffic flow. In [10], we introduced these systems as TTCSs, where the small safe regions are called tracks. Each track is divided into several sub-tracks. The change propagation is a common phenomenon among TTCSs. As a change in the context of a TTCS and its consequent adaptations in the system happen at runtime, several questions arise. For instance, how is the separation between two moving objects guaranteed (safety property)? Regarding the designed adaptation (rerouting algorithm), does the blue aircraft arrive at sub-track 3 at time 9 (qualitative property)? Can the controller design an adaptation plan (select a rerouting algorithm among its algorithms) to satisfy the given properties (synthesis)? These questions can be answered by using verification at runtime. However, TTCSs are large scale and verifying given properties at runtime faces state space explosion. The approach of this paper is our first step toward addressing this problem using compositional verification.

3 Preliminaries

In this section, we briefly recall the definitions of Timed Transition Systems (TTSs) [15] and Timed Input Output Transition Systems (TIOTSs) [9], [16]. We also introduce the coordinated actor models and multiple interactive coordinated actor models as the high-level models whose semantics will be defined based on TTSs.

3.1 Timed (Input/Output) Transition Systems

TTSs are transition systems with the notion of time.

Definition 3.1. (TTS) A TTS is a tuple \( \Pi = (S, s_0, Act, \rightarrow) \), where \( S \) is the set of states, \( s_0 \) is the initial state, \( Act \) is the set of actions, and \( \rightarrow \subseteq S \times (Act \cup \mathbb{R}_{\geq 0}) \times S \) is the transition relation. We use \( s \xrightarrow{a} s' \) instead of \( (s, a, s') \in \rightarrow \). The transition \( s \xrightarrow{a} s' \) is a discrete transition if \( a \in Act \). Otherwise, it is called a timed transition.

TIOTSs are essentially TTSs in which the set of actions is divided into the sets of input actions, output actions, and internal actions. An internal action is denoted by \( \tau \).

Definition 3.2. (TIOTS) A TIOTS with the partitioned action set \( Act = Act_I \cup Act_O \cup \{\tau\} \) is called a TIOTS, where \( Act_I \) and
Act_1_0 are the sets of input and output actions. We use Π = (S, s_0, Act_1, Act_0, \rightarrow) to denote a TIOTS.

3.2 Coordinated Actor Model

Actors are distributed, autonomous objects that interact by asynchronous message passing. In [10], we introduced the coordinated actor model to realize self-adaptive TTCSs. The coordinated actor model as an extension of the actor model encapsulates a set of actors and a coordinator. The coordinator uses a scheduler to govern message passing among the actors. Compared to the actor model, instead of direct message passing among the actors, upon sending a message, an event is created and is placed into the internal buffer of the scheduler. The scheduler selects an event from its buffer based on a given policy and delivers the message to its receiver actor. The same as the actor model, the receiver actors pick and process the delivered messages.

The coordinated actor model is designed based on the MAPE-K feedback loop [18]. Using the MAPE-K feedback loop is a common approach for realizing self-adaptive systems. This control loop consists of the Monitor, Analyze, Plan, and Execute components together with the Knowledge part. The model@runtime is kept in the Knowledge part, is updated by the Monitor component, and is analyzed by the Analyze component. Based on the analysis results, the Plan component makes an adaptation plan that is sent to the system through the Execute component. In [10], the coordinator is extended by a decision maker. The decision maker encompasses the Analyze and Plan activities of the MAPE-K feedback loop. The actors along with the scheduler construct the model@runtime. The decision maker is able to execute the model@runtime to investigate the future behavior of the system. It then applies its decision to the model@runtime and the system.

The coordinated actor model is aligned with the structure of TTCSs, since each sub-track is modeled by an actor, the controller is modeled by a coordinator, and the moving objects are modeled as messages passing among the actors. The controller (coordinator) is able to reroute/reschedule the moving objects considering the congestion and environmental conditions. It also can be augmented with several rerouting/rescheduling algorithms, and by predicting the behavior of the system through executing the model@runtime (analyze), selects the best algorithm for rerouting/rescheduling purpose (plan) [10].

In [11], we developed a Ptolemy template to model and analyze self-adaptive TTCSs based on the coordinated actor model. In our template, each sub-track is modeled by a Ptolemy actor, and the controller is modeled by a Ptolemy director. In this paper, we need to develop a director that not only supports the compositional reasoning, also defines the nondeterministic semantics arisen from the concurrent execution of the actors.

3.3 Multiple Interactive Coordinated Actor Models

Multiple interactive coordinated actor models consist of a coordinated actor model per each subsystem and a top-level coordinator [11]. Each coordinated actor model has its own actor-based model@runtime. The interactions of the coordinators are managed by the top-level coordinator. The message passing among different coordinated actor models is governed by the scheduler of the top-level coordinator. We use the multiple interactive coordinated actor models to build a large-scale TTCS. A TTCS is divided into several control areas. Each area has its own controller and is modeled by a coordinated actor model. In other words, adaptations in a large-scale TTCS cannot be handled by a centralized MAPE-K feedback loop, and developing several interactive MAPE-K feedback loops is necessary.

4 Syntax and Semantics of the Coordinated Actor Model

In this section, we provide formal specifications for the syntax and semantics of the (multiple interactive) coordinated actor model(s). We present the operational semantics of the coordinated actor model (CAM) and multiple interactive coordinated actor models (MICAM) in terms of TIOTSs. We also define parallel composition of two TIOTSs in the context of our study and illustrate it by an example.

4.1 Abstract Syntax of the Coordinated Actor Model

Prior to proposing the abstract syntax of the coordinated actor model, we present the notations used in the rest of this section. Given a set B, B^+ is the set of all finite sequences over elements of B, and P(B) is the power set of B. A coordinated actor model contains a set of actors, a coordinator, and a set of channels. Each connection between two actors is called a channel and includes a queue of messages that are sent by an actor over the channel to another actor.

Definition 4.1. (Channel) A channel is an instance of Channels = ChId × Act × Msg^* × Act, where ChId is the set of all channel identifiers, Act is the set of all actor identifiers, and Msg is the set of all messages in the model.

A channel (ch, i, msgs, j) has the identifier ch and the sequence msgs of messages that are sent from the actor a_i to the actor a_j, where i and j are the identifiers of the actors connected by the channel. Each actor, besides a set of input and output channels, has a set of state variables, the method initialize, and the method handler. The initialize method initializes variables of the actor, and the main computation of the actor is defined in its handler method.

Definition 4.2. (Actor) An actor is an instance of Actors = Act^+ × ChId × Vars × ChId × P(ChId), where Vars is the set of all variable names, and ChId is the set of all statements that can be executed in the model.

An actor a_i = (i, initialize, handler, vars, ChId, ChAct) has the identifier i, the set of state variables vars, and the sets ChId and ChAct of input and output channels, respectively. The initialize and handler methods of the actor are defined as sequences of statements. An actor can send messages over its output channels or read messages from its input channels during the execution of its handler method. Furthermore, the actor can introduce a delay with the amount of t^" by executing the selfCall(t^") statement in its handler and initialize methods. By executing this statement, the actor asks the coordinator to trigger it again after passing t^" units of time. The actor is triggered by calling its handler method.
Each message $msg$ communicated in the model is packaged as an event. An event besides the message $msg$ has a time tag and a reference to the receiver actor in the communication. An event containing no message ($e$) is also generated when an actor executes the $selfCall(t'')$ statement.

Definition 4.3. (Event) An event is an instance of $E = \mathbb{R}_{\geq 0} \times AId \times Msg$.

The event $e = (t', i, msg)$ has a reference to the receiver actor $a_i$. The coordinator stamps the event with the model time $t'$ at which the message $msg$ has been sent. The event $e = (t' + t'', j, e)$ is also generated when the actor $a_j$ executes the $selfCall(t'')$ statement. The coordinator labels the event with $t'$ and $t''$ where $t'$ shows the model time at which the statement is executed. Based on the above description, a set of events with the same time tag can have references to the same actor. For instance, a set of events with the same time tag are created when an actor receives several messages at the same time. The coordinator keeps a global time that denotes the current time of the model. Furthermore, all events are stored in the buffer of the coordinator. Similar to the actors, the coordinator has a set of variables and the method initialize, which initializes variables of the coordinator. The main computation of the coordinator is defined in its schedule method. This method takes events from the buffer of the coordinator and triggers the actors referred to by the events.

Definition 4.4. (Coordinator) The coordinator is an instance of $C = CId \times (Vars \rightarrow \mathbb{R}_{\geq 0}) \times \text{Stm}^* \times \text{Stm}^* \times \mathbb{P} \times (E) \times \mathbb{R}_{\geq 0}$, where $CId$ is the set of all coordinator identifiers.

The coordinator $(cid, vars, initialize, schedule, mtds, EQ, t)$ has the identifier $cid$, the set of variables $vars$, the set of methods $mtds$, the set of events $EQ$, and the model time $t$. The set of methods $mtds$ is defined for planning and analysis purposes. Each method is defined as a sequence of statements. Finally, a coordinated actor model is defined as follows.

Definition 4.5. (CAM) A coordinated actor model $CAM = (A, c, CH)$ contains the set $A$ of actors, the coordinator $c$, and the set $CH$ of channels.

The definition of the multiple interactive coordinated actor models is similar to CAM, given as follows.

Definition 4.6. (MICAM) The multiple interactive coordinated actor models $MICAM = (CA, c, CH)$ contains the set $CA$ of CAMs, the coordinator $c$, and the set $CH$ of channels, where each channel connects two CAMs.

A channel between two CAMs in a model of MICAM is the channel connecting two actors, where the actors belong to different CAMs. We call the coordinator $c$ the top-level coordinator. We also call the coordinator of a CAM in a model of MICAM the lower-level coordinator. The top-level coordinator $c$ keeps a global time as the current time of the model. The current times of all lower-level coordinators are equal to the global time of the top-level coordinator.

4.2 Operational Semantics of the Coordinated Actor Model

The same as many other real-time models, we present the operational semantics of the coordinated actor model in terms of TTS.

Definition 4.7. (CAM Semantics) The operational semantics of $CAM = (A, c, CH)$ is defined as $\Pi = (S_0, Act, \rightarrow)$ such that:

- Each state is an instance of $S = (AId \rightarrow (Vars \rightarrow \mathbb{R}_{\geq 0}) \times \mathbb{N}) \times (CHId \rightarrow \mathbb{M}^*) \times (Vars \rightarrow Val) \times \mathbb{R}_{\geq 0} \times \mathbb{P} \times (E)$, where $Val$ is the set of all possible values of the variables. A state maps each actor of the model to its state variables and a program location $(AId \rightarrow (Vars \rightarrow Val) \times \mathbb{N})$. The program location refers to the currently executing statement of the actor. The state also contains contents of the channels $(CHId \rightarrow \mathbb{M}^*)$, the coordinator variables $(Vars \rightarrow Val)$, the model time $(\mathbb{R}_{\geq 0})$, and the events kept in the buffer of the coordinator $(\mathbb{P}(E))$. For a state $(Atrs, ChS, v, t, EQ)$, $Atrs$ maps each actor to its local state, $ChS$ maps each channel to its sequence of messages, $v$ is the local state of the coordinator, $t$ is the model time, and $EQ$ is the set of events kept in the buffer of the coordinator. The local state of an actor is $(v, pl)$ such that $v : Vars \rightarrow Val$ returns values of state variables of the actor and $pl$ is its program location.

- The values of state variables of the actors and the coordinator in $s_0$ are set based on the statements used in the initialize methods of the actors and the coordinator. For each actor, its program location is zero. The buffer of the coordinator is empty unless the actors use the $selfCall$ statement in their initialize methods. Also, the channels have empty queues and the model time is zero.

- The set of actions is defined as $Act = \{ ch.get() | ch \in CHId \} \cup \{ ch.send(msg) | ch \in CHId \land msg \in \mathbb{M} \} \cup \{ et, assigo, sc, em \}$.

- The transition relation $\Pi \rightarrow S \times (Act \cup \mathbb{R}_{\geq 0}) \times S$ includes the transitions related to a sequence of activities such as advancing the model time, removing the events from the buffer of the coordinator, and triggering the actors. By triggering an actor, the statements of its handler method are executed, while each statement corresponds to a transition. This sequence of activities is performed in the schedule method of the coordinator, and results in the following transitions.

**Time-Progress:** This transition is enabled if the buffer of the coordinator is not empty, all events in the buffer have times greater than the model time, and the program locations of all actors are zero. As a consequence, the coordinator advances the model time to the smallest time of all events in its buffer. The minimum progress of the model time is one unit. This transition is labeled with $d \in \mathbb{R}_{\geq 0}$, where $d$ shows the amount of the time progress.

**Event-Taking:** This transition is enabled whenever there is an event with the time equal to the model time in the buffer of the coordinator. As a consequence, the actor referred to by this event is triggered. If there are more
than one event with the time equal to the model time, the coordinator finds all their corresponding actors and prioritizes them based on a policy. The highest priority actor is then triggered. To this end, all events that have times equal to the model time and refer to the triggered actor are removed from the buffer of the coordinator, while their enclosed messages are added to the end of the queues of the input channels of the actor. Furthermore, the program location of the triggered actor advances from zero to the location of the first statement in a sequence of statements. This sequence that is appended by the endm statement is the body of the handler method of the actor. The endm statement denotes when the handler method terminates. This transition is labeled with et.

Get: This transition is enabled when the program location of the triggered actor refers to the ch.get statement. As a consequence, the first message in the queue of the channel ch is removed, and the program location is updated to the location of the next statement. This transition is labeled with ch.get.

Send: This transition is enabled when the program location of the triggered actor refers to the ch.send(msg) statement. As a consequence, the event \((t, ra, msg)\) is added to the buffer of the coordinator, where t and ra are the current model time and the receiver actor identifier, respectively. Furthermore, the program location is updated to the location of the next statement. This transition is labeled with ch.send(msg).

SelfCall: This transition is enabled when the program location of the triggered actor refers to the selfCall\(t''\) statement. As a consequence, the event \((t + t'', i, e)\), containing no message \(e\), is added to the buffer of the coordinator, where i is the identifier of the current executing actor and t is the current model time. Furthermore, the program location is updated to the location of the next statement. This transition is labeled with sc.

Assignment: This transition is enabled when the program location of the triggered actor refers to an assignment statement. As a consequence, the values of the variables of the actor are changed. Furthermore, the program location is updated to the location of the next statement. This transition is labeled with assign.

End-Method: This transition is enabled when the handler method of the actor terminates. In other words, the program location refers to the endm statement. As a consequence, the program location of the actor is updated to zero. This transition is labeled with em.

As mentioned, the derived semantics for the coordinated actor model is based on TTS. In order to use the compositional verification, we need to determine interfaces of TTSs through which they communicate. To this end, the set of actions of a TTS is partitioned into the input and output action sets \(Act_I\) and \(Act_O\), respectively. Note that the actions that do not belong to the interface of a TTS are modeled as internal actions. A TTS with the partitioned set of actions \(Act = Act_I \cup Act_O \cup \{\tau\}\) is called a TIOTS. To obtain \(Act_I\) and \(Act_O\), we define the sets \(CH_I\) and \(CH_O\) of boundary input and output channels for the coordinated actor model \(CAM = (A, c, CH)\), respectively.

Definition 4.8. (Boundary Input Channel of a CAM) The channel \(ch \in ChId\) is a boundary input channel \((ch \in CH_I)\), if an actor \(a_i \in A\) has \(ch\) as its input channel \((ch \in Ch_I)\) and none of the actors in \(A\) has \(ch\) as its output channel.

Definition 4.9. (Boundary Output Channel of a CAM) The channel \(ch \in ChId\) is a boundary output channel \((ch \in CH_O)\), if an actor \(a_i \in A\) has \(ch\) as its output channel \((ch \in Ch_O)\) and none of the actors in \(A\) has \(ch\) as its input channel.

We transform TTS of a coordinated actor model to its corresponding TIOTS, in which the set \(Act_I\) contains actions of the transitions related to receiving messages from the boundary input channels, and the set \(Act_O\) contains actions of the transitions related to sending messages over the boundary output channels.

Definition 4.10. (TIOTS of a CAM) The TIOTS of a CAM is a TTS whose set of actions is partitioned into \(Act_I = \{ch.get|ch \in CH_I \land ch.get \in Act\}\), \(Act_O = \{ch.send(msg)|ch \in CH_O \land msg \in Msg \land ch.send(msg) \in Act\}\), and \(\tau\) as each element of \(Act\) that does not belong to \(Act_I\) and \(Act_O\).

Note that the timed transitions do not change to \(\tau\) in a TIOTS. Thus, there are four types of transitions in TIOTSs that are input, output, \(\tau\), and timed transitions.

The syntax of the coordinated actor model is inspired by the modeling language of the Ptolemy framework. Also, the semantics of the coordinated actor model is inspired by the Discrete Event (DE) model of computation in Ptolemy. Actors governed by DE communicate via time-stamped events, where events are processed by each actor in a time-stamp order. Events in DE are handled deterministically. In other words, the scheduler of DE has only one choice to order the events (to prioritize the actors to be triggered). Unlike DE, the coordinator in a coordinated actor model is given a policy to handle the events, and consequently we can have a nondeterministic model. Therefore, the model has different execution traces, if the coordinator nondeterministically selects an event among a bunch of events with the same time tag (Event-Taking transition).

Example 1. Consider the multiple interactive coordinated actor models designed for Fig.1(a), in which there is a coordinated actor model for each component of the system. Assume that each sub-track is modeled by a simple actor whose handler method contains the sequence of statements if \((mOb == null)\{ mOb = ch_i.get() , \text{selfCall}(1)\},\) else \((ch_j.send(mOb) , mOb = null)\). The actor contains four input channels and four output channels; i.e. \(ch_i\) and \(ch_j\) are an input and an output channel, respectively. Assume that \(t\) is the current model time. The actor receives a message (corresponding to a moving object), and after one unit of time as the traveling time of the moving object (that is modeled by \(\text{selfCall}(1)\)) sends the message to the next actor. The actor contains the state variable \(mOb\) that shows whether a moving object is passing through the sub-track. The interested reader is referred to [11] to find a more interesting model. Consider that instead of sub-track 8 in Fig.1 sub-track 14 is unavailable, and the purple aircraft is not rerouted. This aircraft arrives at sub-track 9 at time 2 and enters into the component \(C_2\) at time 3. We abstract away the assignment and the endm statements to draw those parts of
TIOTs of the components $C_1$ and $C_2$ in which only the sub-track actors 9 and 10 are triggered, shown in Fig. 2(a) and Fig. 2(b), respectively. In these figures, $s_0$ and $s_0'$ show the initial states of $C_1$ and $C_2$, respectively. $d$ shows the amount of the time progress, $P$ shows the message corresponding to the purple aircraft, $t$ shows the model time, $ch_{i,j}$ denotes the channel connecting two sub-track actors $i$ and $j$, and $EQ$ shows the content of the buffer of the coordinator. For instance, the buffer of the coordinator contains the event $(2, 9, P)$ in state $s_1$ of $C_1$. This event describes that the actor corresponding to sub-track 9 is triggered at time 2 to receive the message $P$. As can be seen, when selfCall($I$) is executed, an event with an empty message is generated for the coordinator, e.g. the event $(3, 9, c)$ in state $s_4$. We will describe Fig. 2(c) in the next section.

### 4.3 The Operational Semantics of the Multiple Interactive Coordinated Actor Models

In the proposed approach, several components affected by a change are adapted and are then composed to form a composite component, which has a model of MICAM. Therefore, we need to define the semantics of MICAM. Similar to the coordinated actor model, the semantics of MICAM is defined based on TTS. For the ease of understanding, we call states of a model of MICAM global states.

**Definition 4.11. (MICAM Semantics)** The operational semantics of $MICAM = (CA, c, CH)$ is defined as $\Pi' = (S', s'_0, Act', -')$ such that:

- Each global state is an instance of $S' = (CAMId \rightarrow S) \times (ChId \rightarrow Msg^*) \times (Vars \rightarrow Val) \times R_{\geq 0} \times P(E)$, where $CAMId$ is the set of all coordinated actor model identifiers, and $S$ is the set of all states of all coordinated actor models. A global state maps each coordinated actor model to its state, defined in Definition 4.7. The global state also contains contents of the channels ($ChId \rightarrow Msg^*$), the top-level coordinator variables ($Vars \rightarrow Val$), the global time ($R_{\geq 0}$), and the events kept in the buffer of the top-level coordinator ($P(E)$). For a global state $(CAtrs, ChSs, v_{t}, t, EQ)$, $CAtrs$ maps each CAM to its state, $ChS$ maps each channel connecting two CAMs to its sequence of messages, $v_{t}$ is the local state of the top-level coordinator, $t$ is the global time, and $EQ$ is the set of events kept in the buffer of the top-level coordinator.

- The values of state variables of the top-level coordinator in $s'_0$ are set based on the statements used in the initialize method of the coordinator. Each CAM has the initial state $s_0$, defined in Definition 4.7. The buffer of the top-level coordinator is empty unless at least a lower-level coordinator has the nonempty buffer. In $s'_0$, the top-level coordinator keeps an event per each lower-level coordinator that has the nonempty buffer. This event is the event with the smallest time tag among the events of the lower-level coordinator. If the lower-level coordinator has several events with the smallest time, one of them, no matter which one, is placed into the buffer of the top-level coordinator. Also, the channels have empty queues and the global time is zero.

- The set of actions is defined as $Act' = Acs \cup \{etT, enf\}$, where $Acs$ is the set of all actions of all CAMs.

- The transition relation $\rightarrow \subseteq S' \times (Act' \cup R_{\geq 0}) \times S'$ includes the transitions related to a sequence of activities such as advancing the global time, removing the events from the buffer of the top-level coordinator, and invoking the schedule method of the lower-level coordinators. This sequence of activities is performed in the schedule method of the top-level coordinator, and results in the following transitions.

**Time-Progress:** This transition is enabled if the buffer of the top-level coordinator is not empty, all events in the buffer of the top-level coordinator have times greater than the global time, an event with the smallest time tag of each lower-level coordinator is kept in the buffer of the top-level coordinator, and the program locations of all actors are zero (none of the actors has been triggered). As a consequence, the top-level coordinator advances the global time to the smallest time of all events in its buffer. It also advances the model times of the lower-level coordinators to the global time. This transition is labeled with $d \in R_{\geq 0}$, where $d$ shows the amount of the time progress.

**Top-Level-Event-Taking:** This transition is enabled whenever there is an event with the time equal to the global time in the buffer of the top-level coordinator. As a consequence, the schedule method of the lower-level coordinator containing that event in its buffer is executed. If there are more than one event with the time equal to the global time in the buffer of the top-level coordinator, the top-level coordinator selects one of them based on a policy (i.e. non-determinism), and executes the schedule method of the lower-level coordinator containing that event in its buffer. The selected event is removed from the buffer of the top-level coordinator. This transition is labeled with $ctT$.

**Actor-Related-Transitions:** The schedule method of a lower-level coordinator is executed whenever two cases hold: there is no event shared between its buffer and the buffer of the top-level coordinator, and there is an event with the current time of the model in its buffer. A CAM is executing whenever besides the first case, the second case
holds or the program location of an actor in that CAM is not zero. Per each transition such as Event-Taking, Get, Send, SelfCall, Assignment, and End-Method, defined in Definition 4.4, a transition is defined in \( \rightarrow' \), when the corresponding CAM in MICAM is executing. Note that in the case that the actor executes the \( \text{ch}.\text{send}(\text{msg}) \) statement, while \( \text{ch} \) is a channel connecting two CAMs, the Send transition is modified as follows. The event \((t, ra, \text{msg})\) is placed into the buffer of the lower-level coordinator of the CAM \( ca \) that contains the actor \( a_{ra} \). Furthermore, this event is placed into the buffer of the top-level coordinator, if \( ca \) is not executing and no event with time \( t \) is shared between the buffer of the coordinator of \( ca \) and the top-level coordinator.

**End-Coordinator-Execution**: This transition is enabled whenever the model time of the lower-level coordinator is equal to the global time of the top-level coordinator, all events of the buffer of the lower-level coordinator have times greater than the global time, no event with the smallest time of the lower-level coordinator is kept in the buffer of the top-level coordinator, and the program locations of the actors in the corresponding CAM are zero. As a consequence, the event with the smallest time in the buffer of the lower-level coordinator is placed into the buffer of the top-level coordinator. If there are several events with the smallest time, one of them, no matter which one, is placed into the buffer of the top-level coordinator. This transition is labeled with \( \text{enf} \).

Similar to the coordinated actor model, we define the sets \( CH_I \) and \( CH_O \) of boundary input and output channels of a model of MICAM, respectively.

**Definition 4.12.** (Boundary Input Channel of MICAM) The channel \( ch \in CH_I \) is a boundary input channel of MICAM = \((CA, c, CH)\) (\( ch \in CH_I \)), if a CAM \( ca \in CA \) has \( ch \) as its boundary input channel and none of the coordinated actor models in \( CA \) has \( ch \) as its boundary output channel. \( \Box \)

**Definition 4.13.** (Boundary Output Channel of MICAM) The channel \( ch \in CH_I \) is a boundary output channel of MICAM = \((CA, c, CH)\) (\( ch \in CH_O \)), if a CAM \( ca \in CA \) has \( ch \) as its boundary output channel and none of the coordinated actor models in \( CA \) has \( ch \) as its boundary input channel. \( \Box \)

We do not define TIOTS of MICAM, since it is similarly defined as TIOTS of a CAM.

### 4.4 Parallel Composition of TIOTSs

Since the proposed approach in this paper is based on composing several TIOTSs, we formally define their parallel composition in this section. Two TIOTSs synchronize on their time progresses if progress in time is jointly performed by both involved TIOTSs. Moreover, they synchronize over their input and output actions, if both of them are jointly involved in performing those actions, which are called handshaking actions.

**Definition 4.14.** (Handshaking Actions) Let \( \Pi_i = (S_i, s_0, Act_i, Act_{O_i}, \rightarrow_i), \ i \in \{1, 2\} \), be two TIOTSs. The actions in the sets \( \{\text{ch}.\text{get} \in Act_i | ch \in CH_I \land \text{msg} \in Msg \land \text{ch}.\text{send}(\text{msg}) \in Act_{O_i}\} \) and \( \{\text{ch}.\text{send}(\text{msg}) \in Act_{O_i} | ch \in CH_I \land \text{msg} \in Msg \land \text{ch}.\text{get} \in Act_i\} \) are called handshaking input and output actions of \( \Pi_i \), respectively. The same definition is used for \( \Pi_2 \). The set of handshaking input and output actions of \( \Pi_1 \) and \( \Pi_2 \) is denoted by \( \text{Act}_{1+2} \).

Based on Definition 4.14, a handshaking input action of \( \Pi_1 \) (i.e. \( \text{ch}.\text{get} \)) corresponds to a handshaking output action of \( \Pi_2 \) (i.e. \( \text{ch}.\text{send}(\text{msg}) \)) and vice versa. The same argument is valid for the handshaking output and input actions of \( \Pi_1 \) and \( \Pi_2 \), respectively. Both \( \Pi_1 \) and \( \Pi_2 \) are jointly involved in performing the handshaking actions and the corresponding handshaking actions are hidden. Our approach to define the parallel composition of TIOTSs is based on the approach of [16], where the notion of parallel composition for the case of TIOTSs of Timed Automata with Inputs and Outputs is introduced. In contrast to the approach of [16], two TIOTSs in our approach do not necessarily have the same amount of the time progresses. Therefore, our approach supports the case in which the progress in time is jointly performed by both involved TIOTSs while one of TIOTSs may progress its time less than the other one. Similar to the approach of [16], in our approach, the timed transitions have lower priorities compared to the transitions labeled with input, output, and internal actions. This way the maximum progress for models in their parallel composition is achieved. We define the parallel composition of two TIOTSs in the context of our study as follows.

**Definition 4.15.** (Parallel Composition) The parallel composition of \( \Pi_1 \) and \( \Pi_2 \) is \( \Pi_1 \parallel \Pi_2 = (S, (s_0, s_0), Act_{1+2}, \rightarrow_{1+2} \), where \( Act_{1} = (Act_{1} \cup Act_{2}) \setminus \text{Act}_{1+2} \) and \( Act_{2} = (Act_{2} \cup Act_{1}) \setminus \text{Act}_{1+2} \). The sets \( S \) and \( \rightarrow \) are the smallest sets such that \((s_0, s_0) \in S \) and the following rules are valid.

1. **Priority over time progress**: For \((s_1, s_2) \in S \) and \( l \in (Act_{1} \cup Act_{2} \cup \{\tau\}) \setminus \text{Act}_{1+2} \), \( s_1 \xrightarrow{l} s_1' \rightarrow s_1' \rightarrow s_1 \Rightarrow (s_1', s_2) \in S \land (s_1, s_2) \xrightarrow{l} (s_1', s_2) \notin \rightarrow \). The same argument is valid for the case of \((s_2, s_1) \in S \land \rightarrow \).

2. **Synchronization on handshaking actions**: For \((s_1, s_2) \in S \) and \( l_1, l_2 \in Act_{1+2} \) such that \( l_1 = \text{ch}.\text{get} \) and \( l_2 = \text{ch}.\text{send}(\text{msg}) \), \( s_1 \xrightarrow{l_1} s_1' \xrightarrow{l_2} s_2 \xrightarrow{l_2} s_2' \Rightarrow (s_1', s_2') \in S \land (s_1, s_2) \xrightarrow{l_1} (s_1', s_2) \xrightarrow{l_2} (s_1', s_2') \rightarrow \). The same argument is valid for the case of \((s_2, s_1) \in S \land \rightarrow \).

3. **Synchronization on time**: For \((s_1, s_2) \in S \) and \( d_1, d_2 \in \mathbb{R}_{\geq 0} \), \( s_1 \xrightarrow{d_1} s_1' \xrightarrow{l_2} s_2 \xrightarrow{d_2} s_2' \Rightarrow (s_1', s_2') \in S \land (s_1, s_2) \xrightarrow{d_1} (s_1', s_2) \xrightarrow{d_2} (s_1', s_2') \rightarrow \). If \( s_1' \) has the smallest time value, \((s_1', s_2') = (s_1', s_2) \). If \( s_2' \) has the smallest time value, \((s_1', s_2') = (s_1, s_2') \). Otherwise, \((s_1', s_2') = (s_1', s_2') \).

If \( t \) is the maximum time value between the time values of \( s_1 \) and \( s_2 \), \( t' \) is the minimum time value between the time values of \( s_1' \) and \( s_2' \), \( d \) is equal to \( t' - t \).

Assume \( s_1 \) and \( s_2 \) are current states of \( \Pi_1 \) and \( \Pi_2 \) and \((s_1, s_2) \in S \). As shown by Rule 3 both of \( \Pi_1 \) and \( \Pi_2 \) have to synchronize on their time progresses in \( \Pi_1 \parallel \Pi_2 \). The states \( s_1' \) and \( s_2' \) in \( s_1 \xrightarrow{d_{1,2} \in \mathbb{R}_{\geq 0}} s_1' \) and \( s_2 \xrightarrow{d_{1,2} \in \mathbb{R}_{\geq 0}} s_2' \) can have different time values if \( d_1 \) and \( d_2 \) are different. To synchronize \( \Pi_1 \) and \( \Pi_2 \), the composition progresses in time to reach the smallest time between the times of \( s_1 \) and \( s_2 \). This time is the global time of \( \Pi_1 \parallel \Pi_2 \). Assume \( s_1' \) has
the smallest time value. To know the amount of the next
time progress in \( \Pi_1 \parallel \Pi_2 \), the current state of \( \Pi_2 \) does not
change. In other words, we have a timed transition from \((s_1, s_2)\) to \((s_1', s_2')\) shown by Rule3. Therefore, the
maximum time between the times of \( s_1' \) and \( s_2' \) shows the
global time. If Rule3 is enabled in \((s_1', s_2')\), \( \Pi_1 \) progresses and its transitions have priority over the timed transition of
\( \Pi_2(s_2 \xrightarrow{d_2 \in \mathbb{R} \geq 0} s_2') \). Note that if \( s_1' \) and \( s_2' \) have the same time
values, we have a timed transition from \((s_1, s_2)\) to \((s_1', s_2')\). Therefore, one of the rules 1 and 2 can be enabled in \((s_1', s_2')\).

There is a case in which the parallel composition of \( \Pi_1 \) and \( \Pi_2 \) reaches the error state \((s_1, s_2)\), where all transitions in \( s_1 \) and \( s_2 \) are labeled with handshaking actions and Rule2 is not valid in \((s_1, s_2)\), or all transitions in \( s_1 \) and \( s_2 \) are labeled with time and handshaking actions, respectively.

**Definition 4.16. (Error State)** The state \((s_1, s_2)\) in the parallel composition is called an error state if none of the rules priority
over time progress, synchronization on handshaking actions, and
synchronization on time are valid in \((s_1, s_2)\).

Two TIOTSs fail to be composed if their parallel composi-
**Definition 4.17. (Composable TIOTSs)** Two TIOTSs \( \Pi_1 \) and \( \Pi_2 \) are called composable if their parallel composition does not reach
an error state.

**Example 2.** The composition of TIOTSs in Fig. 2(a) and Fig. 2(b) is shown in Fig. 2(c). The global time is denoted by \( t \) and \( d \) shows the amount of the time progress when Rule3 is enabled. As can be seen, both TIOTSs synchronize on their time progresses from the state \((s_0, s_0')\). The state of \( C_2 \) does not change since it needs one more unit of time
progress. Then, Rule3 is enabled, and \( C_1 \) proceeds over its state space up to \( s_4 \). Now, both TIOTSs synchronize on one unit of time progress. This results in the state \((s_5, s_1')\).

## 5 Compositional verification of Self-Adaptive TTCSs

In this section, we develop a compositional approach to verify self-adaptive TTCSs in the case of a change occurring and applying adaptation to components. Prior to this, we informally explain our approach on TTCSs. When a TTCS is designed, initial traveling plans of the moving objects are selected in a way that no conflict happens between the moving objects, and the moving objects arrive at their destinations at the pre-specified times. When a change happens to an area, the moving objects arriving at the area with the unavailable sub-tracks in their routes are rerouted. This way the area is adapted. If the moving objects arrive at the adapted area and depart from it based on their initial traveling plans, the correctness constraints of the system are satisfied, and the change propagation stops. Otherwise, the change is propagated to the adjacent areas. The set of correctness constraints in a TTCS includes the moving objects to have arrived at their destinations at the pre-specified times, the fuel of the moving objects should not be less than a threshold, the conflict in the system should be avoided, and the system should be deadlock-free. In the case of propagating the change, all areas affected by the change are adapted, and are
then composed to form a new adapted area. If the moving objects arrive at the new area and depart from it based on their initial traveling plans, the change propagation stops.

We illustrate this approach using an example. Consider a TTCS whose model consists of only two interacting components \( C_1 \) and \( C_2 \). Let \( \Pi = (S, s_0, \{Act_i, \text{Act}_{O_i}, \rightarrow\}) \) be
TIOTS of the component \( C_i \), and Env(C) denotes the set of
environment components of \( C_i \). To ensure that the correctness constraints of the system are satisfied, it is checked whether \( \Pi_1 \) and \( \Pi_2 \) are composable in the absence of a change. None of the correctness constraints is violated and there is a safe execution for the model if \( \Pi_1 \) and \( \Pi_2 \) are composable. By detecting a change, the component affected by the change is adapted. Consequently, a new TIOTS for the adapted component is obtained. Let \( \Pi_{adapt} \) be TIOTS of the adapted component \( C_i \). Suppose that a change in \( C_1 \) is detected. If \( \Pi_{adapt} \) and \( \Pi_2 \) are composable, the provided adaptation in \( C_1 \) does not result in a change propagation to
its environment component \( (C_2) \) and no more adaptation is required. Otherwise, the change is propagated to \( C_2 \). This case shows that the provided adaptation changes the observable behavior of \( C_1 \) and \( C_2 \) has to be adapted to consider the new behavior of \( C_1 \).

Although the proposed approach works effectively for the small systems, in a TTCS with several components, composing TIOTS of the adapted component with TIOTS of its environment components is an expensive process and may result in a large state space. To reduce the state space, we propose considering the observable parts of the environment components. To this end, we define interface processes for a component. The interface processes of a component (or visible parts of its environment) are TIOTS of its environment components in which several transitions are hidden. In other words, only the transitions related to sending the messages from the environment to the component and vice versa are important in the interface processes. The hidden transitions are labeled with \( \tau \). Therefore, an interface process is obtained by restricting TIOTS of an environment component to a set of input and output actions. The restriction operator is defined as follows.

**Definition 5.1.** (Restricted TIOTS) The restriction of \( \Pi \) to a set \( B \) of actions, denoted by \( \Pi \downarrow_\mathcal{B} \) is \((S, s_0, \text{Act}_I, \mathcal{B}_{\text{Act}_O}, \rightarrow)\), where \( \text{Act}_I = \{\text{ch.get}\in \text{Act}_I \land \text{ch.send}(\text{msg}) \in B\} \), \( \text{Act}_O = \{\text{ch.send}(\text{msg})\mid \text{ch.send}(\text{msg}) \in \text{Act}_O \land \text{ch.get} \in B\} \), and all actions in \((\text{Act}_I \cup \text{Act}_O) \setminus (\text{Act}_I \cup \text{Act}_O)\) are transformed to \( \tau \).

To make a reduced TIOTS, we fold up a restricted TIOTS by removing its \( \tau \) transitions. We define a folded TIOTS after defining a finite execution as follows.

**Definition 5.2.** (Finite Execution): A finite execution from the state \( s_i \) in \( \Pi \) is a sequence of transitions from \( s_i \) to a reachable
state \( s_n \), shown by \( s_i \xrightarrow{t_i} s_2 \xrightarrow{t_2} \cdots \xrightarrow{t_{n-1}} s_n \), where \( \forall i, 1 \leq i < n, t_i \in (\text{Act}_I \cup \text{Act}_O \cup \{\tau\} \cup \mathbb{R}_{\geq 0}) \). We use \( \text{exec}_\Pi(s_i) \) to show the set of all finite executions from the state \( s_i \) in \( \Pi \).

**Definition 5.3.** (Folding a Restricted TIOTS): Let \( \Pi = (S, s_0, \text{Act}_I, \text{Act}_O, \rightarrow) \) be the restriction of a TIOTS to a set \( B \) of actions. By folding up \( \Pi \), denoted by \( \Pi \uparrow_\mathcal{B} \), the new TIOTS \( \Pi' = (S, s_0, \text{Act}_I, \text{Act}_O, \rightarrow') \) is obtained as follows.
there is propagated into the component $C_i$ that a change in the component denoted by the arrows between the components. Suppose way. Suppose that messages from its current adaptation is not able to either receive mes-

Example 4. Let Fig. 4 shows the multiple interactive components. The compositional verifica-

Example 3. We restrict TIOTS of Fig. 2(b) to $B = \{ch_{a,10}.send(P)\}$, and then fold it. The resulting TIOTS is shown in Fig. 3. This TIOTS is the interface process of the component whose TIOTS is depicted in Fig. 2(a).

In our example, the interface process of the component $C_1$ is $\Pi_1 \downarrow \text{Act}_{i1} \cup \text{Act}_{o1}$. If $\Pi_1 \downarrow \text{Act}_{i1} \cup \text{Act}_{o1} \parallel \Pi_{a,1}$ does not reach an error state, the change propagation stops. Otherwise, the change is propagated into $C_2$. Note that to reduce the state space, $\Pi_{a,1}$ can also be restricted to the set of input and output actions of $C_2$ and then be folded. In our approach, by propagating the change from a component to its environment components, the environment components affected by the change are adapted. Then, all components affected by the change are composed to create a composite component with the model of the multiple interactive coordinated actor models. It is then checked whether the interface processes of the composite component and its TIOTS are composable.

The structure of track-based systems enables us to focus on a component and define an interface process for each one of its environment components. This way, we are able to find the direction where the change is propagated and to find the components affected by the change propagation. For a better understanding, consider the example below.

Example 4. Let Fig. 4 shows the multiple interactive components. The interactions are denoted by the arrows between the components. Suppose that a change in the component $C_1$ of Fig. 4 is detected and this component (its model/runtime) is adapted. If for each component $C_i$ interacting with $C_1$, $\Pi_i \downarrow \text{Act}_{i1} \cup \text{Act}_{o1} \parallel \Pi_{a,1} \downarrow \text{Act}_{i1} \cup \text{Act}_{o1}$ reaches an error state, the change is propagated into the component $C_i$. It means that $C_i$ with its current adaptation is not able to receive messages from $C_1$ or send messages to $C_1$. In fact, $\Pi_3 \downarrow \text{Act}_{i1} \cup \text{Act}_{o1} \parallel \Pi_{a,1} \downarrow \text{Act}_{i1} \cup \text{Act}_{o1}$ reaches an error state, $C_3$ is not able to receive messages from $C_5$ or send messages to $C_5$. Consequently, $C_3$ should be adapted to provide inputs for $C_3$ or receive inputs from $C_3$ in a different way. Suppose that $\Pi_3 \downarrow \text{Act}_{i1} \cup \text{Act}_{i1} \parallel \Pi_{a,1} \downarrow \text{Act}_{i1} \cup \text{Act}_{o1}$ and $\Pi_2 \downarrow \text{Act}_{i1} \cup \text{Act}_{o1} \parallel \Pi_{a,1} \downarrow \text{Act}_{o1} \cup \text{Act}_{o1}$ reach error states, and the change is propagated into $C_3$ and $C_2$. The components $C_3$, $C_2$, and $C_3$ are adapted and are composed to provide the composite component $C_{1,2,3}$. If $\Pi_5 \downarrow \text{Act}_{o1} \cup \text{Act}_{o1}$

5.1 Correctness of the Proposed Approach

In this section, the correctness of the proposed compositional approach is proved in Theorem. 5.2. This theorem explains that the correctness constraints of the model are preserved whenever there exists an adapted component whose interface processes and its TIOTS are composable. In order to reduce the state space, TIOTS of the adapted component is folded. Therefore, prior to proving Theorem. 5.2, it is proved that a folded TIOTS and its original restricted TIOTS preserve the same set of correctness constraints.

Let $\Pi$ be a restricted TIOTS and $\Pi'$ be its folded TIOTS. Although the non-reachable states are removed from the set $S$ in $\Pi'$, $\Pi'$ and $\Pi$ preserve the same set of correctness constraints. Because there is a weak timed trace equivalence relation between $\Pi$ and $\Pi'$. Two timed transition systems are in the weak timed trace equivalence relation if and only if they have the same traces, ignoring the $\tau$ transitions. Before proceeding with the proof, we define a trace as follows.

Definition 5.5. (Trace) The trace for the finite execution $p = s_0 \xrightarrow{l_1} s_1 \xrightarrow{l_2} \cdots \xrightarrow{l_n} s_n$ is defined as trace$(p) = l_1l_2 \cdots l_n$.

Lemma 5.1. The folding operation preserves the weak timed trace equivalence relation between the original and folded transition systems.

Proof. Based on Definition. 5.3, each finite execution $p = s_1 \xrightarrow{l_1} s_2 \xrightarrow{l_2} \cdots \xrightarrow{l_n} s_{n+1}$ is mapped into the finite execution $p' = s_1 \xrightarrow{l_1} s_{n+1}$. Also, each $p' \in$ exec$(s_1)$ has an extended finite execution $p \in$ exec$(s_1)$, since $\Pi'$ is the
folded TIOTS of \( \Pi \). In both cases, \( \text{trace}(p) = \text{trace}(p') = l_n \) holds. Therefore, \( \Pi \) and \( \Pi' \) have the same sets of traces, ignoring the \( \tau \) transitions.

Since the trace equivalence relation preserves the reachability properties, both \( \Pi \) and \( \Pi' \) satisfy the same set of correctness constraints.

**Theorem 5.1.** The restricted TIOTS and its folded transition system preserve the same set of correctness constraints.

As previously explained, the correctness constraints of the model are satisfied if TIOTS of an adapted component and its interface processes are composable. The adapted component is not necessarily an individual component. It can be created by composing several components.

**Theorem 5.2.** The correctness constraints of the model are preserved if and only if there exists an adapted component \( C_i \) such that for each \( C_j \in \text{Env}(C_i) \), \( \Pi_j \uparrow_{\mathcal{Act}_j \cup \mathcal{Act}_o} \) and \( \Pi_{a,i} \uparrow_{\mathcal{Act}_j \cup \mathcal{Act}_o} \) are composable.

**Proof.** “if”: Suppose that a change happens to the component \( C_i \) and the component \( C \) is adapted. If TIOTS of the adapted component \( C \) and one of its interface processes, e.g. the one that corresponds to the environment component \( C' \), are not composable, the change is propagated to the component \( C'' \). Now, both \( C \) and \( C'' \) are adapted and are composed to form the new component \( C''' \). Assume that TIOTS of the component \( C'' \) and one of its interface processes are not composable. Therefore, the change is propagated into an environment component of \( C'' \). The interface processes of \( C'' \) include the interface processes of both \( C \) and \( C' \). In the approach of this paper, the components affected by the change are gradually composed to form a new component. This procedure continues until a new composite component, e.g. the component \( C_{iv} \), is created, while its TIOTS and its interface processes are composable. This means that there is no more change propagation, and therefore, the correctness constraints of the model are satisfied.

“only if”: By contradiction. Let compositional approach stops composing the components at the point where the correctness constraints of the model are preserved, and assume that there is no adapted component \( C_i \) whose interface processes and its TIOTS are composable. This assumption violates the stopping condition of the approach, since every adapted component have to be composed with its affected environment components. Therefore, the approach stops whenever all components of the model are composed, which results in violating the correctness constraints.

### 6 IMPLEMENTING AND EVALUATING THE APPROACH

In this section, we briefly describe the prototype of the proposed compositional approach. This prototype is implemented in Ptolemy II. We exploit an ATC case study with several control areas to compare the time consumption and the memory consumption between the compositional and non-compositional approaches. Ptolemy II is a modeling framework that provides different models of computation with fully deterministic semantics. As mentioned in Section 4.2, the coordinated actor model has a nondeterministic semantics. Therefore, to explore different execution traces, we implement the coordinator as a director with the nonde-terministic semantics based on TIOTS. Our director provides the assertion-based model checking. It generates the state space of a given component, and performs the reachability analysis. Note that to have a simple model, we develop a model with a single coordinator, because ATC controllers of all areas in our case study have the same adaptation policy (rerouting algorithm). The coordinator in this case has also the role of the top-level coordinator. Therefore, the implemented director generates the state space of the model of an ATC example with several components, where the components are composed to create a new composite component. The rerouting algorithm and the algorithm given in the following section are implemented in the director. It is notable that designing the rerouting algorithm is not the concern of this paper.

#### 6.1 State Space Generation

**Algorithm.** The algorithm uses Depth-First Search (DFS) and Breadth-First Search (BFS) to generate the state space of a given component. We call a state a timed state if a time transition is enabled at the state. The algorithm uses a queue to store the timed states. It triggers the actor which can be triggered in the initial state of the component to generate the next state. The initial state has several outgoing transitions (resp. several next states) if several actors can be triggered at the state. The next state is put into the queue if the state is a timed state. Otherwise, the actors which can be triggered in the next state are triggered. Therefore, the algorithm uses DFS to generate all the traces starting with the initial state and ending with the timed states. It then uses BFS to process the timed states stored into the queue. It dequeues a timed state, and similar to the initial state, uses DFS to generate all the traces starting with that state and ending with the new timed states.

The algorithm to generate the state space of a given component terminates whenever one of the following conditions is fulfilled: all the moving objects supposed to travel through the component depart from it (reach their destinations), a disaster happens (i.e. the fuel of a moving object is zero), and the analysis time passes a threshold. It is notable that the state space of a TTCS does not have a Zeno behavior, since the minimum progress of the time in our model of a TTCS is assumed one unit.

**Composition.** Assume that a storm happens at time \( t \), and the component \( C_1 \) is affected by the storm. Also, assume that flight plans of the aircraft are not necessarily the initial flight plans and have been adjusted based on the data monitored from the system. We use flight plans of the aircraft to extract the state of the system, describing positions of the aircraft in the traffic network at time \( t \). We then set the initial state of \( C_1 \) to the state of the system. Similarly, we use flight plans of the aircraft to obtain states of boundary actors of the environment components of \( C_1 \) by identifying the aircraft entering into \( C_1 \) in the future. These boundary actors will directly send messages to \( C_1 \) at times \( t', t'' \geq t \). To generate the state space, we first compose \( C_1 \) with boundary actors of its environment components to create a new composite component.
is performed in the level of the coordinated actor model. We then use the above algorithm to generate the state space of the composite component. If, as mentioned in Section 4.3, the composition of the state spaces of $C_l$ and the boundary actors does not reach an error state, the state space of the composite component is successfully generated. Suppose the case in which the composition reaches an error state. In this case, assume that a boundary actor of the environment component $C_2$ is not able to send its message at the pre-specified time $t''$, $t'' \geq t$, to $C_1$. This means that the change is propagated from $C_1$ to $C_2$ at time $t''$. We repeat the same procedure as $C_1$ to set the state of $C_2$ to the state of the real system at time $t''$. We also set states of those boundary actors that send messages to $C_2$ at the times greater than $t''$. Therefore, from $t''$ on, we have a component, composed of $C_1$, $C_2$, and several boundary actors, whose state space is generated. This procedure terminates whenever the algorithm reaches a state in which all moving objects supposed to travel across their positions and cannot proceed over their routes. Using the described method, we obtain 40 experiments in which none of the approaches face a deadlock, and model checking

6.2 Experimental Setting

For the comparison purpose, we focused on an ATC example with a $n \times n$ mesh map, where the location of each sub-track is shown by the pair $(x, y)$ in the mesh. We also considered $2 \times (n - 1)$ source airports (each one is connected to a sub-track whose location is the pair $(0, i)$ or $(i, 0)$, $0 \leq i < n$), and $2 \times (n - 1)$ destination airports (each one is connected to a sub-track whose location is the pair $(n - 1, i)$ or $(i, n - 1)$). We developed an algorithm to generate the initial flight plans of $m$ aircraft, and an algorithm (an adaptation policy) to reroute the aircraft as follows.

**ALG1: Generating the initial plans.** This algorithm randomly generates the source $(x_s, y_s)$, the destination $(x_d, y_d)$, and a departure time from the source airport for each aircraft. The departure times follow an exponential distribution with the parameter $\lambda$. The time difference between two subsequent departures from a source airport should not be less than the flight time $FD$, which shows the traveling time of an aircraft across a sub-track. The aircraft $A$ can travel through the sub-track with the location $(x, y)$ if $A$ has no time conflict with the aircraft $B$, which is also supposed to travel across $(x, y)$. Similar to the XY routing algorithm [19], ALG1 attempts to find a route from $(x_s, y_s)$ to $(x_d, y_d)$ by first traversing the X dimension and then traversing the Y dimension of the mesh. ALG1 switches its traversing direction from X to Y whenever the aircraft has a time conflict with another aircraft along the X dimension. ALG1 backtracks if it can move across none of the dimensions from the location $(x, y)$. It then moves across the Y dimension. These procedure continues until a route is discovered. ALG1 does not guarantee to find the efficient (e.g. shortest) route.

**ALG2: Rerouting algorithm.** Assume that the aircraft is going to leave the location $(x_0, y_0)$ and the rest of its route is \[ [(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)] \]. Also, assume that the sub-track $T$ with the location $(x_1, y_1)$ is unavailable, and the moving object is not able to travel through it. In the ATC example, a sub-track is unavailable if it is stormy or is occupied by another aircraft. The algorithm finds a neighbor of $(x_0, y_0)$, e.g. the sub-track $T'$, that is available and neither of its $x$ and $y$ is equal to $T$. Then, the algorithm tries to find a route from $T'$ in several steps. At the first step, the algorithm tries to find a route with the length 2 from $T'$ to $(x_2, y_2)$. If there is no such route, it attempts to find a route with the length 3 from $T'$ to $(x_3, y_3)$, and so on. If a route from $T'$ to $(x_i, y_i)$, $2 \leq i \leq n$, is found, the route is concatenated with the current route of the aircraft from $(x_{i-1}, y_{i-1})$ to $(x_n, y_n)$. In fact, ALG2 attempts to find a route with the length equal to the length of the initial route. However, if $(x, y)$ does not have an available neighbor, or a route with the same length as the initial route is not found, the algorithm finds a route from a neighbor (the neighbor in this case might be occupied). Then, the aircraft will stay one more unit of time in $(x, y)$, and will fly based on its new route. If no route is found, the moving object will stay one more unit of time in $(x, y)$, and then will fly based on its initial route.

The rerouting algorithm uses the same procedure as ALG1 to find a route. It first traverses the X dimension and then traverses the Y dimension of the mesh. In contrast to ALG1, ALG2 does not check the time conflict of the aircraft in the future, and therefore backtracking is not needed. Because, we will take care of the conflict by rerouting the aircraft the moment a potential conflict is detected. However, ALG2 does not select a stormy sub-track as a part of its route.

**Scenarios.** We perform three sets of experiments: (ES1) that is to compare the time and memory consumptions between the compositional and non-compositional approaches, (ES2) that is to depict the variation of the time consumption in a set of experiments for each approach, and (ES3) that is to compare the scalability of the approaches. In our experiments, the traffic networks in (ES1) and (ES2) have the same configuration. We consider a $9 \times 9$ and a $15 \times 15$ mesh structure as our traffic networks in (ES1) and (ES3), respectively. These meshes are respectively divided into 9 regions of $3 \times 3$ and 9 regions of $5 \times 5$. We assume that the fuel of each aircraft is more than the length of the longest path in the traveling network, and is set to 200, 200, and 325 in (ES1), (ES2), and (ES3), respectively. The threshold of the analysis time is an hour. We also assume that a storm happens in the middlemost sub-track of the networks. In (ES1), we use ALG1 to generate 135 batches of flight plans per each $\lambda$ in $\{0.5, 0.25, 0.125\}$, where $\lambda$ is the parameter of the exponential distribution to generate departure times of the aircraft from source airports. Each batch contains flight plans of 1000 aircraft. Per each batch $P_{ij}, 1 \leq i \leq 135$, we generate 10 batches $P_{ij}, 1 \leq j \leq 10$, of flight plans, such that $P_{i1}$ contains the first 100 flight plans of $P_i$, $P_{id}$ contains the first 200 flight plans of $P_i$, and so on. We use both approaches to analyze each batch $P_{ij}$ per each time of the storm in $\{100, 200, 400, 600, 800\}$. We remove the batch $P_i$ from the experiments of both approaches if for a batch $P_{ij}$ and a time of the storm, the model in one of the approaches is not deadlock-free, or its model checking time passes a threshold. We set the threshold to an hour. In the case of TTCs, a deadlock occurs when the moving objects take their positions and cannot proceed over their routes. Using the described method, we obtain 40 experiments in which none of the approaches face a deadlock, and model checking
times of both approaches are less than the threshold. In our experiments, per each \( j \), we calculate the averages of the analysis time and the number of states of the batches \( P_{ij} \).

In (ES2), we use the batches of flight plans generated in (ES1) for \( \lambda = 0.5 \). We use both approaches to analyze each batch \( P_i \), while the storm happens at time 100. Each batch contains the flight plans of 1000 aircraft. The model of the system is not deadlock-free for 18 batches of flight plans that are removed from experiments of the both approaches. Furthermore, the analysis times of 2 batches are not less than an hour using the compositional approach, while this number is 20 in the non-compositional approach. The experiments with the analysis time more than an hour in one of the approaches is removed from the experiments of both approaches. We then illustrate the variation of the analysis time in the set of remaining experiments for each approach.

In (ES3), we use ALG1 to generate a batch \( P \) of 7000 flight planes with \( \lambda = 0.5 \). We assume that the change happens at time 100. In (ES3), we start with the first 100 flight plans of \( P \), and gradually increase the number of flight plans to compare the scalability of two approaches. The scalability of the approaches is measured by the number of the aircraft. To this end, we define a threshold for the model checking time and set this threshold to an hour. The approach that can analyze a model with more number of the aircraft in less than the defined threshold is more scalable.

In our experiments, we assume that FD as the traveling time of an aircraft across a sub-track is one. We also assume that the aircraft consumes one unit of fuel per one unit of the traveling time.

6.3 Comparison

Different parameters such as the rerouting algorithm, the time of the storm, the place of the storm, the network traffic volume, the amount of concurrency arisen from flight plans of the aircraft, and the network dimension change the results of experiments. Because the traffic network of the ATC domain has a cascaded architecture, the place of the storm can be typically approximated as the middle of the traffic network. Therefore, we select the middlemost sub-track of the network as the place of the storm. We change the network traffic volume and subsequently the concurrency contained in the model through different \( \lambda \)s (the inverse of the mean interval time between two departures).

We run our experiments on an ubuntu 18.04 LTS amd64 machine with 67G memory and Intel (R) Xeon (R) CPU E5-2690 v2 @ 3.00GHZ. A part of our experimental results are shown in Figures 5, 6, 7, and 8. In these figures, “C” and “NC” refer to the compositional and non-compositional approaches, respectively. The legend entry \( C - i \), \( i \in \{100, 200, 400, 600, 800\} \) depicts the experimental results of the compositional approach for the time \( i \) at which the storm happens. The legend entry \( NC - i \) depicts the results for the non-compositional approach. As shown in Fig. 5 and Fig. 3 using the compositional approach results in decreasing the model checking time and the number of states. As expected, by increasing the number of aircraft, the number of states and accordingly, the model checking time increase. The same results are valid for the smaller value of the time at which the storm occurs, since a few number of the aircraft have arrived at their destinations when the storm happens. By increasing the time at which the storm occurs, the differences between the results of the compositional and non-compositional approaches decrease. It is because, most of the aircraft have arrived at their destinations when the storm happens late. To have a better representation of the model checking time difference between the compositional and non-compositional approaches, we depict the results of the model checking time for \( \lambda = 0.5 \) in two diagrams with two different time scales, shown in Fig. 8. As can be seen, the compositional approach is able to model check a model with 1000 aircraft in a few seconds for the smallest value of the time at which the storm happens. More experiments on comparing the model checking time of the compositional and non-compositional approaches are available.

The results of our experiments in (ES2) are shown in Fig. 7. The variation of the model checking time in a set of experiments with no deadlock when the compositional approach is used is shown in Fig. 7(a). The results of the same experiments for the case in which the non-compositional approach is used are depicted in Fig. 7(b). We also depict the variation of the time needed to detect a deadlock in a set of experiments using the compositional and non-compositional approaches in Figs. 7(c) and 7(d), respectively. As shown in Fig. 7(a), excluding the outliers, the model in our experiments is analyzed in less than 23 seconds using the compositional approach, while this time is around 818 seconds in the non-compositional approach. Also, in our experiments, the compositional approach detects a deadlock in around 2 minutes.

The results of our experiment in (ES3) are shown in Fig. 8. To compare the scalability of both approaches, we run both approaches for the same scenario. Furthermore, we define a threshold for the model checking time and set this threshold to an hour. As can be seen, the non-compositional approach is not scaled for more than 1000 aircraft. The results of the compositional approach in Fig. 8 have fluctuations appeared between 1400 to 2200 aircraft and also between 3200 to 3600 aircraft. By adding new aircraft to the traffic network, some areas are congested, and consequently the concurrency of the model increases. This event results in some fluctuations and the fast growth of the “C” plot between 1400 to 2200 aircraft. This plot has a normal growth from 2200 to 3200 aircraft, since by adding the new aircraft, the behaviors of the congested areas has not sensibly changed. By adding 200 aircraft to the traffic network, the aircraft are rerouted in a way that the congestion in some areas decreases. This event results in decreasing the number of states.

7 Related Work

In this section, we concentrate on three classes of most related studies. The first class is concerned about modeling and verifying Traffic Control Systems (TCSs). The second class describes the most closely related work to our verification approach, and the third class is about formal analysis of self-adaptive systems at runtime. Finally, we briefly explain the major contributions of this work compared to the related work.

2. www.ce.sharif.ir/~mbagheri/TTCs.zip
Fig. 5: The number of states in (ES1) for each value of $\lambda$ in \{0.5, 0.25, 0.125\}, where $\lambda$ is the parameter of the exponential distribution to generate the departure times of the aircraft. The notations $C$ and $NC$ refer to the compositional and non-compositional approaches, respectively. The time at which the storm happens varies in the set \{100, 200, 400, 600, 800\}. As an instance, $C-100$ depicts the results of the compositional approach when a storm occurs at time 100.

Fig. 6: The model checking time in (ES1) for $\lambda = 0.5$. The left side depicts the model checking time in the compositional (C) and non-compositional (NC) approaches when a storm occurs at a time in \{100, 200\}. The right side depicts the model checking time of each approach when a storm occurs at a time in \{400, 600, 800\}. The right and the left side figures show the model checking time with different scales.

Fig. 7: The model checking time in (ES2) for $\lambda = 0.5$. The storm occurs at time 100. The variations of the time needed to model check the experiments with no deadlock using the compositional (C) and non-compositional approaches (NC) are depicted in parts (a) and (b), respectively. The variations of the time needed to detect a deadlock using both approaches are depicted in parts (c) and (d).
Modeling and Verifying TCSs. TCSs such as ATC and train control systems, due to the tight interconnection of the physical plant and the controller software, are mostly categorized as hybrid systems. There is a vast literature on verifying dynamic models of TCSs to detect the future conflicts among the moving objects \([20, 21, 22]\), to resolve the potential conflicts through the trajectory planning \([23, 24]\), and to evaluate the correctness of the communication protocols among different entities of the system \([25, 26, 27]\). In these approaches, the moving objects, e.g., aircraft or trains, along with their operational details are the concern of modeling. As an instance of this kind of modeling, the model of a train control system is created by composing a set of hybrid automata, where each automaton is the model of a train. Modeling the dynamic behaviors of each moving object in these approaches needs a set of differential equations, which due to the large number of the moving objects, makes the analysis of TCSs difficult \([28]\).

In contrast to the mentioned approaches, the regions of the traveling space, e.g. the sub-tracks in TTCSSs, are the concern of modeling in our approach. Although this kind of modeling may lose some operational details of the moving objects, it is more appropriate for modeling rerouting/rescheduling the moving objects \([29]\). In other words, the adaptation of a TTCSS is concerned with aggregate behaviors of the moving objects, and affects the whole traffic network by rerouting/rescheduling the moving objects \([29]\). Therefore, by modeling each sub-track as an actor, we develop a one-dimensional model of the traveling space instead of a complex multi-dimensional model of the moving objects. The properties of our interest such as preventing a moving object from running out of the fuel, and the arrival of a moving object at its destination at a pre-specified time are handled by adding a few features to the message corresponding to the moving object. For instance, each message carries information about the remaining fuel of the moving object for the rest of its travel, or carries the designated time for the arrival of the moving object at each sub-track in its route. This approach of modeling not only provides an acceptable fidelity for the problem \([11]\), but also relieves the analysis difficulties.

Compositional Methods. A compositional verification method is proposed in \([8]\), where each component of the model is supplied with a correctness property and an abstraction of its environment is modeled by interface processes. Then, by composing a component with its interface processes and verifying a property over the composition, the satisfaction of the property over the whole system is proved. Consider two components \(P_1\) and \(P_2\) with the alphabet \(\Sigma_{P_1}\) and \(\Sigma_{P_2}\). The restriction of \(P_1\) to \(\Sigma_{P_2}\), shown by \(P_1 \downarrow \Sigma_{P_2}\), is the interface process \(A_1\). Compositional verification using the approach of \([8]\) is formulated as: \(A_1 \equiv P_1 \downarrow \Sigma_{P_2} \land \psi \in L(\Sigma_{P_2}) \land A_1 \parallel P_2 \parallel P_1 \parallel P_2 \parallel \psi\), where \(L\) is a logic for reasoning. Unlike this approach, we do not need to define the correctness properties for the components of the model. In our approach, the model has a set of correctness constraints based on the pre-defined plans of the moving objects. The time constraints and the deadlock-freedom are preserved if the interface processes of the adapted component and its TIOTS are composable. The conflict avoidance in our approach is built in the coordinated actor model, since each sub-track is a critical section \([11]\). Furthermore, if the fuel level becomes less than a threshold, a notification is raised in the model. Therefore, there is no need to express the correctness constraints with a logical formula.

In \([30]\), an Assume-Guarantee based approach for verifying self-adaptive systems at design time is proposed. In \([30]\), the changed component is adapted. Then, a backward reasoning starts and re-generates a new assumption for the adapted component. If the new assumption is weaker than the previous assumption of the component, the adaptation is correct. Otherwise, the reasoning continues on the context of the changed component. If it reaches a null assumption on the context of the system, the adaptation is incorrect. The paper focuses on safety properties of the system, and does not consider the change propagation. The work in \([9]\) defines a refinement relation and a weakening operator to check the satisfaction of a property over a real-time system. Each property is divided into a set of subspecifications for which an assumption and a guarantee are defined. The subspecifications, assumptions, and guarantees are defined by Timed Input/Output Automata (TIOA). The assumption
and guarantee are combined into a contract using the weakening operator. The property is satisfied if subspecifications refine their corresponding contracts and vise versa. This approach is not proposed for verifying self-adaptive systems at runtime and consequently does not consider the change and its effects on the system. Unlike [30] and [9], which define an assumption and a guarantee for each component, we only define the interface processes.

Magnifying-Lens Abstraction (MLA), presented in [31], copes with the state space explosion in obtaining the maximal probabilities over a Markov Decision Process (MDP). It partitions the state space into regions, and calculates the upper and lower bounds for the maximal reachability or safety properties on the regions. It magnifies on a region at a time and obtains the values of mentioned parameters by calculating their values for each concrete state. Unlike MLA, the bounds of sub-properties in our approach are given through the interface processes and are re-generated by adapting the components. Furthermore, verifying the model regarding the change propagation phenomenon is not a concern in [31].

Formal Analysis of Self-adaptive Systems at Runtime. A set of approaches such as [1], [2], [4], [5], [6], [32] use the state-based models (that are defined by states and transitions) to verify self-adaptive systems at runtime. Incremental runtime verification of MDPs, described in the PRISM language, is proposed in [2], where runtime changes are limited to vary parameters of the PRISM model. An MDP is constructed incrementally by inferring a set of states needed to be rebuilt. The constructed MDP is then verified using an incremental verification technique. Runtime verification of parametric Discrete Time Markov Chains (DTMCs) is accomplished in [1]. In this method, probabilities of transitions are given as variables. Then, the model is analyzed and a set of symbolic expressions is reported as the result. By substituting real values of the variables at runtime, verification is reduced to calculating the values of the symbolic expressions.

In [32], a self-adaptive software is designed as a dynamic software product line (DSPL). Then, an instance of DSPL is chosen at runtime considering the environmental changes. This approach uses parametric DTMCs to model common behaviors of the products and each variation point separately. Therefore, there is no need to verify each configuration separately. RINGA, a self-adaptive framework for runtime verification of self-adaptive systems, is proposed in [5]. RINGA uses Finite State Machines (FSM) to develop a design-time model of a self-adaptive system, and abstracts the model for using at runtime. Each state of the model implements a module of the system, while a transition triggers an adaptation. Each transition is assigned an equation that is parametrized by the environmental variables. The value of the equation is calculated at runtime. Lotus®runtime [4] is a tool for verifying self-adaptive systems at runtime. It uses Probabilistic Labeled Transition Systems (PLTS) to develop a model®runtime. It monitors the generated execution traces of the system and updates the probabilities in PLTS. The desirable properties in [4] are explained through a source state, a target state, a condition to be satisfied, and the probability of satisfying the constraints.

In comparison with the state-based models, an actor model is in a higher level of abstraction. Our actor-based approach besides decreasing the semantic gap between the model®runtime and our problem domain applications (there is a one-to-one mapping between elements of the system and the model), facilitates modular analysis of TTCs.

The failure propagation is studied in [33] that checks whether the structural adaptation of the system is fast enough to prevent a hazard. Each adaptation takes an amount of time during which the failure is propagated through the system. After an adaptation, it is checked whether the remaining failures in the system lead to a hazard. Compared to the approach of [33], our approach, besides detecting a hazard, assures the satisfaction of the time constraints of the system. Based on the circumstances existing at the time the change occurs, different values of latency for different adaptation policies can be imposed on the model by defining a threshold over the analysis time in our approach. It is supposed that the human is involved if the adaptation cannot be handled during the expected time. The latency-aware adaptation is studied in [6], where a probabilistic model checker proactively selects an adaptation strategy to maximize the utility of the system. Unlike [6], our focus is on effectively verifying the system behavior.

The approach of this paper was specifically proposed for TTCs. It checks at runtime whether, regarding the environmental changes, the rerouting/rescheduling (adaptation) results in a disaster or in violation of the safety and timing constraints of the system. It also introduces the notion of the change propagation, and uses the idea of the compositional verification to investigate how far a change is propagated, how far the system needs more adaptations, and how many components of the system should be analyzed. In other words, our approach gives the idea of containing the change in the smallest area of the traveling space by selecting the rerouting algorithm that adheres to the timing constraints of the system. Therefore, we assume that the planner of a self-adaptive TTCs is always able to find a safe plan within the adaptation scope if such a plan exists. This assumption is realized by the planner if it tries several adaptation plans and selects the most appropriate one [11]. To the best of our knowledge, this paper is the first work on verification of self-adaptive TTCs at runtime.

8 Conclusion and Future Work
We proposed an approach in which the model of the system is decomposed into a set of components. Upon encountering a change, the component affected by the change is adapted. If TIOTS of the adapted component and its interface processes are composable, the change does not propagate. Otherwise, the environment components affected by the change propagation are adapted. Then, all components affected by the change are composed to create a composite component. The same process is repeated for the composite component. We model each component by a coordinated actor model, whose semantics is defined based on TIOTS. We use the
reduced version of TIOTSs in checking the composability, where only the transitions related to sending messages from the environment to the component and vice versa are considered.

The correctness constraints in our approach are built into the model. They are preserved if TIOTS of the adapted component and its interface processes are composable. When a change happens to a component, different adaptation policies are investigated. An adaptation policy may contain the change, and the change does not propagate to the environment components. Therefore, it is possible that the change propagation stops at a time in the future. However, in the worse case that the change propagates to the whole system, all components are composed in our approach. We implemented our approach in the Ptolemy II framework. The results of our experiments confirm that our approach decreases the model checking time and the number of states. To improve our approach, we will study the system behavior in several time windows in the case of propagating the change through the whole system as the future work.

ACKNOWLEDGMENTS

The work on this paper has been supported in part by the project “Self-Adaptive Actors: SEADA” (nr. 163205-051) of the Icelandic Research Fund. The authors would like to thank professor Edward A. Lee for his valuable suggestions.

REFERENCES

[1] A. Filieri and G. Tamburrelli, “Probabilistic verification at runtime for self-adaptive systems,” in Assurances for Self-Adaptive Systems, ser. LNCS, J. Câmara, R. de Lemos, C. Ghezzi, and A. Lopes, Eds., 2013, vol. 7740, pp. 30–59.
[2] V. Forejt, M. Kwiatkowska, D. Parker, H. Qu, and M. Ujjma, “Incremental runtime verification of probabilistic systems,” in Runtime Verification, ser. LNCS, S. Qadeer and S. Tasiran, Eds., 2013, vol. 7687, pp. 314–319.
[3] M. U. Iftikhar and D. Weyns, “Activforms: Active formal models for self-adaptation,” in Proceedings of the 9th International Symposium on Software Engineering for Adaptive and Self-Managing Systems, ser. SEAMS 2014. ACM, 2014, pp. 125–134.
[4] D. M. Barbosa, R. G. D. M. Lima, P. H. M. Maia, and E. Costa, “Lotus@runtime: A tool for runtime monitoring and verification of self-adaptive systems,” in 2017 IEEE/ACM 12th International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS), May 2017, pp. 24–30.
[5] E. Lee, Y.-G. Kim, Y.-D. Seo, K. Seol, and D.-K. Baik, “Ringa: Design and verification of finite state machine for self-adaptive software at runtime,” Information and Software Technology, vol. 93, no. Supplement C, pp. 200 – 222, 2018.
[6] G. A. Moreira, J. Câmara, D. Garlan, and B. R. Schmerl, “Proactive self-adaptation under uncertainty: a probabilistic model checking approach,” in Proceedings of the 2015 10th Joint Meeting on Foundations of Software Engineering, ESEC/FSE 2015, Bergamo, Italy, August 30 - September 4, 2015, pp. 1–12.
[7] A. Pnueli, In Transition From Global to Modular Temporal Reasoning about Programs, 1985, pp. 123–144.
[8] E. M. Clarke, D. E. Long, and K. L. McMillan, “Compositional model checking,” in Logic in Computer Science, LICS’89, Proceedings, Fourth Annual Symposium on. IEEE, 1989, pp. 353–362.
[9] A. David, K. G. Larsen, A. Legay, M. H. Møller, U. Nyman, A. P. Ravn, A. Skou, and A. Wkowsksi, “Compositional verification of real-time systems using ecdar,” International Journal on Software Tools for Technology Transfer, vol. 14, no. 6, pp. 703–720, Nov 2012.
[10] M. Bagheri, I. Akkaya, E. Khamespanah, N. Khakpour, M. Sirjani, A. Movaghar, and E. A. Lee, “Coordinated actors for reliable self-adaptive systems,” in Formal Aspects of Component Software: FACS 2016, O. Kouchkarenko and R. Khosravi, Eds., 2017, pp. 241–259.
[11] M. Bagheri, M. Sirjani, E. Khamespanah, N. Khakpour, I. Akkaya, A. Movaghar, and E. A. Lee, “Coordinated actor model of self-adaptive track-based traffic control systems,” Journal of Systems and Software, vol. 143, pp. 116 – 139, 2018.
[12] C. Ptolemaeus, System Design, Modeling, and Simulation: Using Ptolemy II. Ptolemy. org Berkeley, CA, USA, 2014.
[13] M. Bagheri, E. Khamespanah, M. Sirjani, A. Movaghar, and E. A. Lee, “Runtime compositional analysis of track-based traffic control systems,” SIGBED Rev., vol. 14, no. 3, pp. 38–39, Nov. 2017.
[14] North atlantic operations and airspace manual, International Civil Aviation Organization (ICAO), 2016.
[15] C. Baier and J.-P. Katoen, Principles of Model Checking (Representation and Mind Series). The MIT Press, 2008.
[16] M. Krichen and S. Tripakis, “Conformance testing for real-time systems,” Formal Methods Syst. Des., vol. 34, no. 3, pp. 238–304, Jun. 2009.
[17] G. Agha, Actors: A Model of Concurrent Computation in Distributed Systems. Cambridge, MA, USA: MIT Press, 1986.
[18] J. O. Kephart and D. M. Chess, “The vision of autonomic computing,” Computer, vol. 36, no. 1, pp. 41–50, Jan 2003.
[19] S. D. Chawade, M. A. Gaikwad, and R. M. Patrakar, “Review of xy routing algorithm for network-on-chip architecture,” International Journal of Computer Applications, vol. 43, no. 21, pp. 975–887, 2012.
[20] L. de Alfaro, X. Wang, X. C. Zhang, J. Yang, and X. Li, “Toward online hybrid systems model checking of cyber-physical systems’ time-bounded short-run behavior,” SIGBED Rev., vol. 8, no. 2, pp. 7–10, Jun. 2011.
[21] H. A. P. Blom, J. Krystul, and G. J. Bakker, “A particle system for safety verification of free flight in air traffic,” in Proceedings of the 2016 IEEE Conference on Decision and Control, 2016, pp. 1574–1579.
[22] R. Chen, J. Zhou, B. Chen, and Y. Song, “Model-based verification method for solving the parameter uncertainty in the train control system,” Reliability Engineering and System Safety, vol. 145, pp. 169 – 182, 2016.
[23] S. M. Loos, D. Renshaw, and A. Platzer, “Formal verification of distributed aircraft controllers,” in Proceedings of the 16th International Conference on Hybrid Systems: Computation and Control, ser. HSCC’13. ACM, 2013, pp. 125–130.
[24] K. Margetelos and J. Lygeros, “Toward 4-d trajectory management in air traffic control: A study based on monte carlo simulation and reachability analysis,” IEEE Transactions on Control Systems Technology, vol. 21, no. 5, pp. 1820–1833, 2013.
[25] W. Damm, A. Mikschl, J. Oehlerking, E.-R. Olderog, J. Pang, A. Platzer, M. Segelken, and B. Wirtz, Automating Verification of Cooperation, Control, and Design in Traffic Applications. Springer Berlin Heidelberg, 2007, pp. 115–169.
[26] Y. Zhao and K. Y. Rozier, “Formal specification and verification of a coordination protocol for an automated air traffic control system,” Science of Computer Programming, vol. 96, pp. 337 – 353, 2014, special Issue on Automated Verification of Critical Systems (AVoCS 2012).
[27] “Performance analysis and verification of safety communication protocol in train control systems,” Computer Standards and Interfaces, vol. 33, no. 5, pp. 505 – 516, 2011.
[28] P. K. Menon, G. D. Sweriduk, and K. D. Bilimoria, “New approach for modeling, analysis, and control of air traffic flow,” Journal of guidance, control, and dynamics, vol. 27, no. 5, pp. 737–744, 2004.
[29] E. A. Lee and M. Sirjani, “What good are models?” in Formal Aspects of Component Software, K. Bae and P. C. Olveczky, Eds. Springer International Publishing, 2018, pp. 3–31.
[30] P. Inverardi, P. Pelliccione, and M. Tivoli, “Towards an assume-guarantee theory for adaptable systems,” in Proceedings of the 16th International Conference on Hybrid Systems: Computation and Control, ser. HSCC 2013. ACM, 2013, pp. 125–130.
[31] D. R. Chark, “Autonomous vehicles,” in Intelligent Transportation Systems: Principles, Models, and Techniques, J. Câmara, R. de Lemos, C. Ghezzi, and A. Lopes, Eds., 2013, pp. 112–151.
Maryam Bagheri received the M.S. degree in computer engineering from Sharif University of Technology, Tehran, Iran, in 2013. She is currently working toward the Ph.D. degree in computer engineering at the Department of Computer Engineering at Sharif University of Technology.

Marjan Sirjani is a Professor and chair of Software Engineering at Mlardalen University, and the leader of Cyber-Physical Systems Analysis research group. She is also a part-time Professor at School of Computer Science at Reykjavik University. Her main research interest is applying formal methods in Software Engineering. She works on modeling and verification of concurrent, distributed, and self-adaptive systems. Marjan and her research group are pioneers in building model checking tools for actor models.

Ehsan Khamespanah is a graduate student from a double-degree program in the ECE Department at Tehran University and the department of computer science at Reykjavik University. He is a Postdoctoral Researcher in Software Architecture and Formal Methods lab at Tehran University. His research interests include formal methods, software testing, cyber-physical systems, and software architecture. Ehsan has a BE in computer engineering form Tehran University.

Ali Movaghar received the B.S. degree in electrical engineering from the University of Tehran, in 1977, and the M.S. and Ph.D. degrees in computer, information, and control engineering from the University of Michigan, Ann Arbor, in 1979 and 1985, respectively. He is a professor in the CE Department, Sharif University of Technology, in Tehran, Iran. His research interests include performance/dependability modeling and formal verification of distributed real-time systems. He is a senior member of the IEEE and the ACM.