The Formal Specification Column

by

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Formal Modeling and Analysis of Mobile Ad Hoc Networks and Communication Based Systems using Graph and Net Technologies*

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Abstract

During the last decade, mobile and flexible communication based systems have become more and more important. In our research project "Formal modeling and analysis of flexible processes in mobile ad-hoc networks" (forMA$_l$NET*) we have proposed an adequate formal modeling technique due to the integration of Petri nets and Petri net transformations called reconfigurable systems and algebraic higher order nets. In this article we review graph and net transformations in order to state the requirements of a formal modeling technique for mobile and flexible communication based systems. In the main part we present an overview over our research project and show how the results are realizing these requirements.

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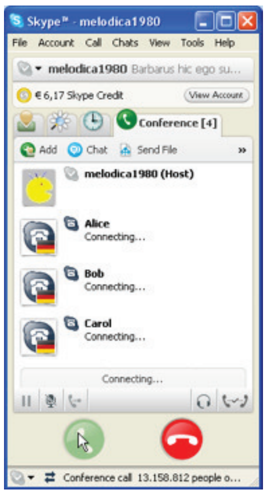
1 Introduction

In the context of concurrent and distributed systems Petri nets, first introduced by C.A. Petri in [40], are a well-known and widely used formalism and have been employed in practical applications in many different areas (see e.g. [44, 45, 32, 33, 51, 2]). Their graphical representation and formal semantics excellently support the modeling, simulation, and formal analysis of such systems. High-level net classes are obtained by combining Petri nets with an appropriate data type part. Despite the large variety of different high-level net classes, this thesis is based on three of them in particular. Most prominent are coloured Petri nets [26, 27, 28], a combination of Petri nets and a high-level programming language, which is an extension of the functional programming language Standard ML [34]. Coloured Petri nets offer formal verification methods and an excellent tool support, which has been used in numerous case studies within a large variety of different application areas. Apart from this there are algebraic high-level nets [38, 13], which give rise to a formal and well-defined description due to their integration of classical algebraic specifications into Petri nets.

The research area of graph transformation [46, 9] is a discipline of computer science which dates back to the early seventies. Methods, techniques, and results from the area of graph transformation have already been studied and applied in many fields of computer science such as formal language theory, pattern recognition and generation, compiler construction, software engineering, concurrent and distributed systems modelling, database design and theory, logical and functional programming, AI, visual modelling, etc. Graph transformation has at least three different roots, namely from Chomsky grammars on strings to graph grammars, from term rewriting to graph rewriting, and from textual description to visual modelling. This theory has already been generalized to net transformations systems in [11, 8], including high-level and low-level nets.

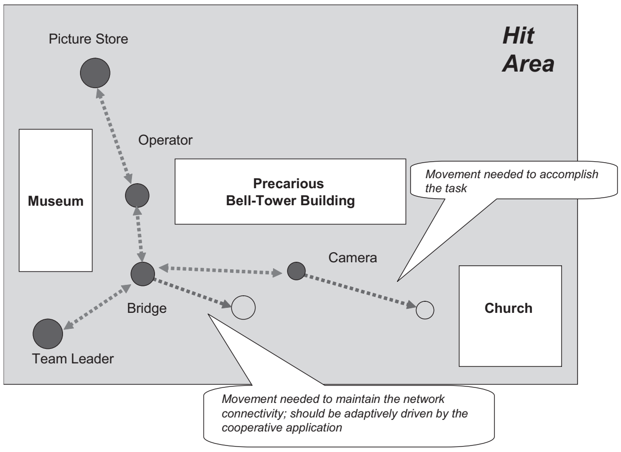
An application oriented Petri net technology for modeling communication based systems has been systematically developed in [18]. Since then communication based systems are enhanced particularly with regard to flexibility and mobility. In flexible and mobile communication based systems, communicating actors, can transmit content, which is contextually interpreted. Actors may join, move in or leave networks, where the actors' preferences, access rights and roles are respected and define a temporary set of communicating partners and a context of interpretation for communicated data.



Communication nowadays is based on Internet platforms like Skype, which offers many typical features of flexible communication based systems. Skype is a widely used program for Internet telephony, offering easy to use (synchronized) data exchange and conferences. With its contact and privacy management, users can decide who and how other users can contact them.

Besides infrastructure-based networks mobile ad-hoc networks [1] are used to support network's topology for a group of people coming together for a short time to share data. Mobile Ad-hoc NETworks (MANETS) are networks of mobile devices that communicate with one another via wireless links without relying on an underlying infrastructure; this distinguishes them from other types of wireless networks, e.g., cell networks or infrastructure-based wireless networks. In order to achieve communication, each device in a MANET acts both as an endpoint and as a router forwarding messages to devices within radio range.

As a motivating example, the reader should consider an emergency scenario in archaeological disaster/recovery [6]: after an earthquake, a team (led by a team leader) is equipped with mobile devices (laptops and PDAs), and sent to the affected area to evaluate the state of archaeological sites and the state of precarious buildings; the goal is to draw a situation map in order to schedule restructuring jobs. In a typical cooperative process the team is considered as an overall MANET, in which the team leader's device coordinates the other team member devices, by providing suitable information (e.g., maps, sensible objects, etc.) and assigning activities. But in a particular scenario, it could happen that the movement of the camera device equipped would result in a disconnection from the others. To predict such a situation the team leader selects a possible "bridge" device to follow (i.e., to move afterwards) the "going-out-of-range" operator/device, thus maintaining the connection and ensuring a path among devices. This in general may result in a change of the MANETS topology. In such a way the team leader, on the basis of the disconnection prediction, schedules the execution of new and not previously scheduled activities. Specifically, the team leader transforms the current workflow in order to adapt it to the evolving network topology.



Conventional modeling techniques for communication based systems like UML [36] are restricted to model communication based on a static, immutable network topology. These techniques do not support visual modeling and visual behavior simulation. Research on MANETS has focused mainly on the infrastructure at the four lower levels of the ISO/OSI-standards (e.g. [30, 31, 47]) and modeling techniques are mainly developed for the network topology e.g. mobility issues as in [7, 48].

Normally workflows in flexible and mobile communication based systems are not fixed once and for all at design time but constantly adapted at run time predicting disconnections or reorganizing activities. From a practical point of view processes in this area often have to be restructured e.g. because of unforeseen events or to maintain the network connectivity resulting in a highly dynamical modification of processes. In several applications the adaption of processes depends on specific informations, thus, there is the need for explicit data modeling. Multicasting is a typical communication concept of communication spaces, where one actor transmits content to a group of selected actors, enabling conference connections or group chats, but the number of actors is not known a priori. This requires on the one hand a suitable description of distributed workflows and on the other hand expressive techniques for the adaption.

Especially in mobile environments movement activities concerning the network connectivity should be separated from activities concerning the intended process, so that the different parts should fit together in an consistent way. In flexible and mobile communication based systems at least two levels should be distinguished: the object level concerning the intended workflows and the system level representing the network topology. Note, that both levels are effected by dynamical modifications to adapt them to changing environments and it is important to know whether these modification are independent or in conflict. As workflows at the object level can evolve in two different ways, the notions of conflict and concurrency become more complex. Assume that a given workflow represents a certain system state. The next evolution step can be obtained not only by execute certain sets of activities but also by workflow adaption. Hence the question arises whether each of these evolution steps can be postponed after the realization of the other, yielding the same result, and if they can be performed in a different order without changing the result.

Thus in our research project forMA$_l$NET, we propose an integration of graph transformation concepts and Petri nets as a fundamental, visual and formal modeling framework for mobile and flexible communication based systems. The rest of this paper gives an overview over an adequate formal modeling technique in flexible and mobile communication based systems (Section 2) and important results (Section 3).

2 Formal Modeling of Mobile Ad Hoc Networks and Communication Based Systems

Petri nets are a fundamental, visual and formal modeling technique in concurrency and have been subject for suitable extensions in particular to model reconfigurations of the net structure and the exchange of data. Thus they are profitably applied to model workflows in mobile ad-hoc networks and flexible communication based systems (see [6, 43, 50, 49, 24]). In more detail we propose an appropriate integration of Petri nets, graph transformation concepts [46] and algebraic specification techniques [16] to yield low level and high level Petri net transformations [14, 9] using net transformation rules to adapt the net structure to changing requirements of the system.

2.1 Petri Net Transformations as Adhesive High Level Replacement Systems

Petri nets that can be transformed during run time allow a formal description of dynamic changes. We use rules and transformations for P/T systems in the sense of the double pushout approach for graph transformation [9]. The basic idea behind net transformation is the stepwise development of P/T systems by given rules. Think of these rules as replacement systems where the left hand side is replaced by the right hand side while preserving a context. For suitable applications of such rules specific control structures are additionally needed [43]. These conditions restrict the application of rules forbidding a certain structure to be present before or after applying a rule in a certain context. Adhesive high-level replacement systems [9] are a suitable categorical framework for double pushout transformations. In [10, 43] we have instantiated adhesive high-level replacement systems by appropriate categories of low level as well as high level nets in order to achieve net transformations in a more elegant way.

2.2 Reconfigurable Place/Transition Systems

In [23, 15, 42, 24], the concept of reconfigurable P/T systems has been introduced that is most important to model changes of the net structure while the system is kept running. In detail, a reconfigurable P/T-system consists of a P/T system and a set of rules, so that not only the follower marking can be computed but also the structure can be changed by rule application to obtain a new P/T system that is more appropriate with respect to some requirements of the environment. Moreover these activities can be interleaved. In [19, 35] we have extended reconfigurable P/T nets on the one hand by marking changing Petri net transformations, and on the other hand by a technique parallelizing the application of net transformation rules at several matches at once. Both extensions together allow a flexible modeling of communication concepts in communication spaces, like e.g. multicasting, where one actor transmits contents to a group of selected actors.

2.3 Integration of Graph and Net Technologies with Algebraic Specification

The integration of Petri nets with data type descriptions has led to powerful specification techniques (a summary can be found in [29]). In [23] we have introduced the paradigm "nets and rules as tokens" by a high level net model with suitable data type part in the sense of algebraic specifications [16]. The model called algebraic higher order (AHO) net [21, 6, 25] exploits some form of topology to control rule applications and token firing. In general an AHO net is defined by an algebraic high level net [17, 41], where the marking is given by suitable net systems respectively rules. As in MANETS and communication based systems there is a need for a explicit data exchange, we also have not only low level net systems but also high level net systems as tokens. In [25] we have related these two net classes in order to analyze the firing and transformation properties of the corresponding net class transformation defined as functors between corresponding categories of AHO nets.

In [6, 37, 49, 3, 19] we have shown that these approaches are powerful enough to cover the main aspects of MANETS and flexible communication based system by integrating Petri nets (topology), abstract data types (content spaces), and net transformations (interaction).

2.4 Layered Architectures using Algebraic Higher Order Nets

In [39, 37, 5, 3] we have presented a layered architecture of AHO nets that allows the separation of support activities concerning the network from activities concerning the intended workflow. This yields better and conciser models, since supporting the network connectivity has a much finer granularity than the more or less fixed workflow execution. The layered architecture of AHO nets distinguishes three layers, the workflow layer, the mobility layer and the team layer. The workflow layer describes the overall workflow that is to be achieved by the whole team. The mobility layer describes the workflows in order to maintain the MANETS connectivity. The team layer describes the individual activities of the team members. Moreover, we provide a set of rules in each layer for the transformation of corresponding P/T systems expressing different system states.

3 Analysis of Net Transformations

For reconfigurable systems and AHO nets we have achieved extensive results covering the transfer of the well known results for graph transformation systems not only to net transformation systems but also to the interaction of net transformations and token firing, different degrees of consistency of layered architectures and the equivalence and composition of high level net processes as an adequate semantics of AHO nets.

3.1 Main Results for Graph and Net Transformation Systems

Within the framework of adhesive HLR systems there are many interesting results concerning the applicability of rules, parallel and sequential dependence and independence, embedding and extension of transformation steps and concurrency of rule applications [9]. The concept of parallel independence states that two transformation steps are not in conflict while two consecutive transformation steps are sequentially independent if they are not causally dependent. Provided that the relevant conditions are satisfied two alternative transformation steps may be swapped and each of them can still be applied after the other has been performed. Sequentially independent transformation steps can be put into one parallel transformation step having the same effect. But if sequential dependencies occur a so called concurrent rule can be constructed establishing the same effect in one transformation step as the whole transformation sequence. Moreover under certain conditions transformations can be embedded into larger contexts. Since P/T systems as well as AHL systems form a weak adhesive HLR category [10, 43, 41], we can apply these results to reconfigurable P/T systems and AHO nets.

3.2 Independence of Net Transformations and Token Firing

Based on the observation of parallel and sequential independence of rule applications the main results in [15, 42, 22] deals with conflict situations between transformation and token firing. The traditional concurrency situation in P/T systems without capacities is that two transitions with overlapping pre domain are both enabled and together require more tokens than available in the current marking. As P/T systems can evolve in two different ways the notions of conflict and concurrency become more complex. Assume that a given P/T system represents a certain system state. The next evolution step can be obtained not only by token firing but also by the application of one of the rules available. Hence the question arises whether each of these evolution steps can be postponed after the realization of the other, yielding the same result, and if they can be performed in a different order without changing the result. We have presented conditions for parallel and sequential independence and we have shown that provided that these conditions are satisfied, firing and transformation steps can be performed in any order, yielding the same result. Moreover, we have correlated these conditions, i.e. that parallel independence implies sequential independence and vice versa, sequential (coparallel) independence implies parallel and coparallel (parallel and sequential) independence. The advantage of the presented conditions is that they can be checked syntactically and locally instead of semantically and globally. Thus, they are also applicable in the case of complex reconfigurable systems.

The extension of reconfigurable P/T systems to marking changing Petri net transformations and individual tokens (see in [19, 35]) allows for modeling the token firing of a P/T system by an appropriate transition rule having the same effect. In this way the independence of transformation and firing steps can be directly analyzed using the main results for graph and net transformation systems in Subsection 3.1.

3.3 Composition of High Level Net Processes

The main ideas and results in [12, 20] concern the composition of high level net processes [13], an adequate semantics for AHO nets. In general the composition of high level net processes is not a high level net process, because the composition may contain forward and/or backward conflicts and also the partial order might be violated. Thus we state suitable conditions, so that the composition of high level processes leads to a high level process. We have introduced the concept of equivalence of high-level net processes, where the net structures of these high level net processes might be different, but they have especially the same input/output behavior. Hence their concurrent computations are compared in the sense that they start and end up with the same marking, but even corresponding dependent transitions may be fired in a different order. In this context the main problem solved is to analyze the independence of high level net processes, i.e. under which condition high level processes can be composed in any order leading to equivalent processes.

3.4 Consistency of Layered Architectures

As we distinguish different layers in which transformations are applied independently, we have investigated in [39, 37, 5, 3] how these layers fit together. Layer consistency means that these layers together form a valid AHO net model of workflows in MANETS. In a mobile setting it is not realistic to expect consistency at all moments, so there are different degrees of inconsistency that are feasible during maintenance of consistency. The notions and results concern the fundamental understanding of the subsequent possibilities for maintaining consistency in MANETS. Checking consistency means that in all states of the AHO net modeling the workflows in MANETS consistency can be checked. Guaranteed consistency is given if each state of the AHO net is a consistent one, that is the rules are only applied when the conditions that guarantee consistency are satisfied. Backtracking consistency is the possibility to reach an inconsistent state, and to have then the possibility to backtrack the transformations until a consistent state is reached. Restoring consistency is the possibility of inconsistent states in the AHO net, but with a recipe to fix them. This recipe provides conditions for the application of the next transformations. Consistency maintenance depends on the precise AHO net model controlling the way rules are applied during token firing.

4 Conclusion

In this paper we have given an overview over the main concepts and results concerning an adequate formal modeling technique for flexible and mobile communication based systems in our research project forMA$_{\text{l}}$NET. As the first phase of the project has succeeded, in the second phase we currently solve major problems concerning the analysis of processes of AHO nets and investigate extended consistency concepts of layered AHO nets. We have implemented an Eclipse-based tool environment for reconfigurable Petri nets, which currently allows modeling, simulation and analysis of reconfigurable P/T nets [4]. An extension of our tool to AHL nets with individual tokens and amalgamation is planned for the future. Although we have achieved several important results towards a formal modeling framework for flexible and mobile communication based system, there is still a lot of research to be done, especially for further application areas like ambient living and Google Wave.

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