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Simulation of a Clustering Scheme for Vehicular Ad Hoc Networks Using a DEVS-based Virtual Laboratory Environment

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Abstract

Protocol design is usually based on the functional models developed according to the needs of the system. In Intelligent Transport Systems (ITS), the features studied regarding Vehicular Ad hoc Networks (VANET) include self-organizing, routing, reliability, quality of service, and security. Simulation studies on ITS-dedicated routing protocols usually focus on their performance in specific scenarios. However, the evolution of transportation systems towards autonomous vehicles requires robust protocols with proven or at least guaranteed properties. Though formal approaches provide powerful tools for system design, they cannot be used for every types of ITS components. Our goal is to develop new tools combining formal tools such as Event-B with DEVS-based (Discrete Event System Specification) virtual laboratories in order to design the models of ITS components which simulation would allow proving and verifying their properties in large-scale scenarios. This paper presents the models of the different components of a VANET realized with the Virtual Laboratory Environment (VLE). We point out the component models fitting to formal modeling, and proceed to the validation of all designed models through a simulation scenario based on real-world road traffic data.

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Keywords: Vehicular Networks; Routing Protocol; Intelligent Transport Systems; DEVS; Event-B

1. Introduction

Wireless communication technologies are one of the key factors for the development of the Internet of the future (connected objects, autonomous vehicles and smart cities). Ad hoc network paradigm, particularly, provides high flexibility by offering the possibility of short-range communications between all connected nodes without any pre-existing communication infrastructure. The intrinsically decentralized coordination of an ad hoc network makes its safety, robustness and performance highly dependent from the protocols used. The goal is to ensure the discovery of the nodes in the network, their self-organization and routing, and also the quality of service and security of their exchanges. The connected objects can adopt an opportunistic functioning by communicating via an infrastructure when it is operational or switching to ad hoc mode when the infrastructure fails. The Internet protocols initially de-

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signed for best-effort applications are confronted with the requirements of traditionally more sensitive applications, such as logistics or tactical units, transport, industrial platforms, e-health, etc. Facing the variety of the requirements that all these applications may present, it is necessary to develop fast and effective evaluation and validation tools, from the earliest steps of the protocol design. The objective of our work is to extend a virtual laboratory based on multi-modeling in order to simulate the communication systems dedicated to transport, and especially, the protocols dedicated to ad hoc communications between the vehicles. The targeted approach consists in three phases from the design to the evaluation of the vehicular ad hoc network protocols:

- Step 1: formal modeling of the components that support formal specification (eg. the routing protocol, etc). This modeling makes it possible to verify and prove the properties of the related components (for the protocol this may concern convergence, quality of service or security properties) by resorting to formal methods and tools (eg. B and Event-B);
- Step 2: integrating the formal models into a larger simulation, by the means of multi-modeling: transforming the formal models (from Event-B) into DEVS models (Discrete Event System Specification), and connecting them to the models of the other components of the transport system (eg. the vehicular ad hoc network);
- Step 3: integrating real-world data into DEVS simulation and managing the interactions with other specialized simulators for the different components (eg. MATLAB for propagation models, OPNET or NS3 for communications, SUMO for mobility models, etc). The goal is to achieve realistic evaluations of the entire system.

In this paper, the work focuses on the presentation of the models of a vehicular ad hoc network realized with a DEVS-based virtual laboratory environment (VLE). The rest of this paper is organized as follows. After a brief review of the literature in section 2, the proposed approach is described in section 3. The models currently developed are explained in section 4. The results of their validation are presented in section 5.

2. Related work

Several works propose various approaches to design and evaluate the protocols for ad hoc communications in vehicular networks. This review only illustrates the main trends in these approaches through representative examples.

2.1. Ad hoc routing protocols

The numerous ad hoc routing protocols¹ identified in the literature² can be grouped into a limited number of approaches. The first one concerns reactive protocols (DSR, AODV, etc.). In this approach, the vehicles compute the routes on-demand according to the traffic to send³. These protocols do not continually maintain network topology. As a result, they generate less routing traffic. However, since the route computation starts only when the traffic has to be sent, this often leads to higher delays, which is not suitable for real-time applications and high mobility environment such as vehicular ad hoc networks. Another family of protocols identified as proactive (OLSR, etc.) permanently maintains a structure in the network topology. These protocols compute periodically the routes ready to use when traffic arrives for one of the known destinations⁴. Though they are convenient for highly dynamic environments, these protocols are more prone to routing traffic overhead when the network is dense. Thus, they generally implement a clustering scheme in order to reduce the effects of broadcast transmissions, including that related to routing traffic, and avoid congestion. The last approach developed concerns the so called geographical protocols (GRP, etc.). These protocols use information on the geographic location of the vehicles in order to organize the routing of the data⁵. However, they assume the existence of a centralized location service which provides to each vehicle the positions of all the other vehicles. A such assumption does not cope with pure ad hoc networks where no infrastructure should be needed. They are more likely to serve in infrastructure-based or mixed vehicular networks.

2.2. Routing protocols evaluation

Most of the evaluations performed on ad hoc routing protocols focus on measuring the performance obtained based on a set of metrics in specific scenarios. The issues mainly addressed in these studies are the following:

- In particular conditions of density, mobility and given a communication technology, what performance profile can the protocol guarantee to the various vehicular network applications?
- For a set of possible configurations of the vehicular network, does the protocol allow all the time to satisfy a set of requirements according to a set of metrics (delay, bandwidth, loss rate, etc.)?
- By varying both network configurations and the application requirements, how both the protocol behavior and the application performance vary?

The results obtained through this type of evaluations generally lead to a qualitative and quantitative appreciation on the performance of the protocol. However, they are not performed to obtain the proofs on the protocol intrinsic properties. One of the studied properties concerning ad hoc network protocols is the convergence of the protocol, otherwise its ability to complete its tasks and deliver a stable network structure in a given time. Another property is the robustness which reflects its ability to rebuild its structure and maintain its functionalities despite the changes in the network. A third property studied is its scalability (in terms of vehicle density or traffic load). We are particularly interested by the properties related to quality of service⁶ or security⁷. These latter are the most crucial for guaranteeing an increased interest for ad hoc communications in future and effective vehicular ad hoc networks.

2.3. Contribution of formal approaches

The adoption of wireless technologies in transportation systems has been concerned with formal methods in their earlier stages, since most of these systems impose stringent safety requirements. The European Train Control System (ETCS), to mention few, contains a set of safety applications modeled and verified using B formalism. The testings for verifying that the GSM-R (Global System for Mobile communications in Rail) could meet ETCS requirements were conducted over four years before a final adoption. Many formal approaches have been also proposed for the analysis of the routing protocols for vehicular ad hoc networks. Other authors⁸ propose a methodology for verifying the properties related to security in network protocols⁹. Singh et al.¹⁰ present a formal model of AODV with Event-B. Another study¹¹ concerns a similar model of the DSR protocol in order to prove its properties related to security. Finally, Kamali et al.¹² describe a set of Event-B refinements of a formal model of the OLSR protocol. Two problems persist with formal approaches in network protocol design for intelligent transport systems, and suggest an approach combining formal methods with discrete event simulation:

- The first concerns the joint evaluation of components which are prone to formal modeling with the other components of the ITS which are not adapted to such approach. The tools such as Event-B can only evaluate formal models, while the simulation tools based on multi-modeling allow connecting heterogeneous models and devices in a single simulation-based evaluation process;
- The second problem is related to the scalability of the formal tools. Though they provide some extensions that can animate formal models, they do not support large scale animation of a great number of interacting objects, which would be mandatory in order to verify the behavior of systems such as ITS and VANETS.

Therefore, two approaches can apply: introducing DEVS mechanisms into formal tools or coupling formal models using DEVS based tools. Yacoub et al.¹³ propose to integrate the DEVS mechanisms into the formal modeling tool PROMELA. They partially solve the problems related to scalability, but not those involving interactions with non-formal models since all the components should be modeled with PROMELA. We investigate the other solution.

3. Projecting formal models into DEVS multi-modeling

The proposed approach consists in developing a methodology in order to integrate formal models in DEVS-based multi-modeling. As shown in figure 1, this methodology operates in two phases:

- The first phase consists in modeling some components using formal tools such as Event-B in order to obtain a set of proofs using the automatic prover, and a set of proof obligations that necessitate an interactive proving process involving an expert (denoted here by RPO for Residual Proof Obligations);

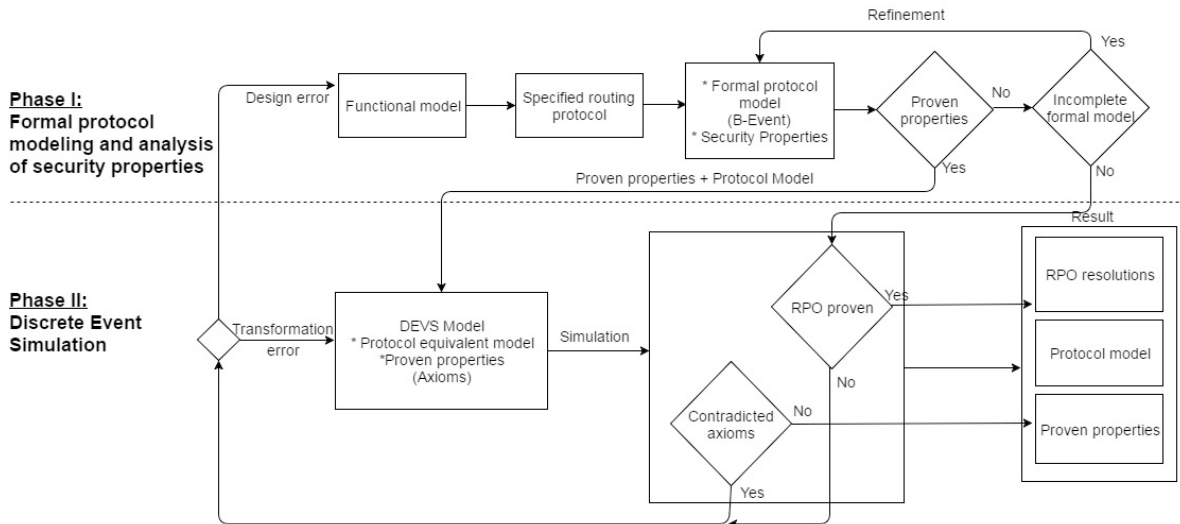


Fig. 1. Main steps of a methodology for enhancing the proven properties of ITS components using Event-B and DEVS simulation¹⁴

- In the second phase, the formal models, the proven properties and the RPOs are transferred into a DEVS multi-modeling, which integrates the models of the components that do not fit to formal modeling. Then a simulator generated from the multi-modeling allows evaluating the entire system through a discrete event simulation.

This approach will allow obtaining proven properties through formal tools. It will also address the issue of interacting with the components that are not prone to formal modeling, and that of large-scale scenarios. Moreover, it will allow detecting design errors in formal models when the simulation results are in contradiction with some theorems. Finally, it may help increasing the number of proven properties if the simulation results bring new data that allow solving the RPOs. However, the implementation of this approach raises some issues that need to be addressed :

- Building automatically a DEVS representation of the models, the related proven properties and the RPOs obtained using the formal tool (Event-B). This issue raises itself several implementation problems.
- Designing the DEVS multi-modeling in such a way that the simulation results allow verifying the properties that were proven in the formal tool, and also producing data that could be used in an interactive proving process.

4. DEVS models of VANET components

A first step in the development of the proposed approach is to implement a DEVS-based multi-modeling of all the components used to simulate an ITS (e.g. a VANET). The DEVS modeling that we propose, is based on two variants of the DEVS formalism: P-DEVS¹⁵ (Parallel-DEVS) and DS-DEVS¹⁶ (DEVS Dynamic Structure). The first variant manages simultaneous external events and internal transitions by introducing the conflict function. The notion of transient state is also implemented by resorting to zero lifetime events. DS-DEVS and its improvements like DS-DE¹⁷ introduce the possibility to modify the graph model during the simulation. For example, it is possible to create and destroy atomic or coupled models, or to create and destroy connections between the models. In our case, all these possibilities, which are not available in the classical DEVS formalism, are fundamental. Indeed, we chose, for the moment, to represent a vehicle as an atomic model whose connections represent the communication channels of the vehicles in the ad hoc network. The second important aspect is the management of the vehicles movements in a 3D continuous space (the road traffic lanes). Several space management options exist: discretization of the space which raises the problem of the discretization step, distributing the space definition within each model (vehicle) or centralizing the definition and the management of the space into a specialized model. We chose the third option. As shown in Figure 2 , the model “space” collaborates with the model “controller” which has a special type: it is an

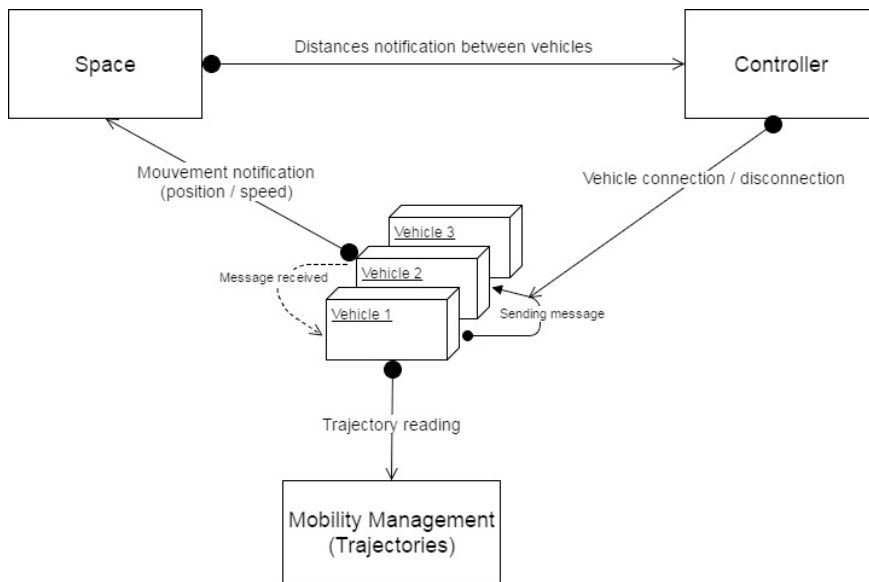


Fig. 2. Ad hoc network: a DEVS model

executive from the point of view of DS-DEVS. An executive is an atomic model, unique within a coupled model, that can modify the structure of the coupled model. All these operations are performed by the abstract algorithm of the associated coordinator so that we can guarantee the causality. The couple “space”-“controller” is responsible for: location management of the vehicles, the detection and dynamic creation of potential connections between the vehicles and the appearance and disappearance of the vehicles in the studied section of traffic lane according to their respective trajectory. The “space” model is notified by the “controller” when a vehicle enters or leaves the section. The “space” model calculates the connections based on the changes in the speed and direction sent by each vehicle.

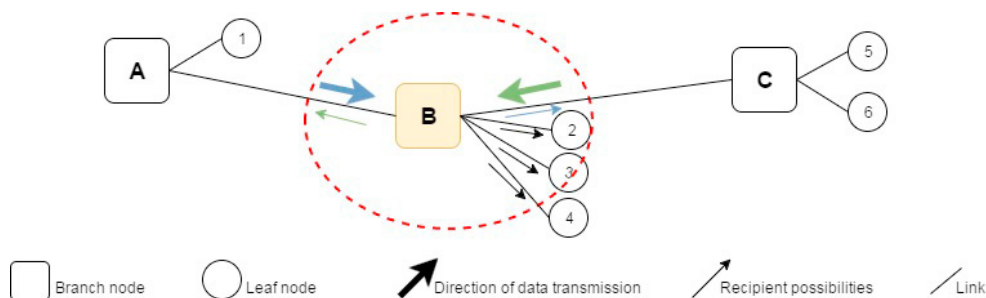


Fig. 3. VANET topology and traffic structuring with the CBL (Chain-Branch-Leaf) scheme

For each new connection, the “controller” is notified and it updates the connection graph. Depending on its connections, the “vehicle” model transmits and receives messages that allow it to execute the routing protocol and the clustering method. As discussed in 2.1, proactive routing protocols offer a bigger range of possibilities because they maintain a local topology of the network. So, we chose a variant of the OLSR protocol that implements the clustering algorithm Chain-Branch-Leaf (CBL)¹⁸. As described in Figure 3, CBL builds a chain formed by particularly stable vehicles called “branch” to which attach vehicles located in their coverage area, called “leaf”. Through OLSR routing messages, the vehicles exchange information that allows each one deciding in a completely distributed way if it is a branch or a leaf. Each vehicle which is a leaf designates the branch to which it is attached. As for the MPR in native OLSR, when a broadcast message is sent, it is retransmitted only by the vehicles called “branch” A, B, C. In addition, CBL realizes an additional optimization which makes it possible to indicate that a broadcast message must be flooded

only upstream (blue arrow) or downstream (green arrow) in the chain. The “vehicle” component including its routing protocol (OLSR implementing the clustering scheme CBL) is a component that can be modeled using formal tools.

5. Validation of the models

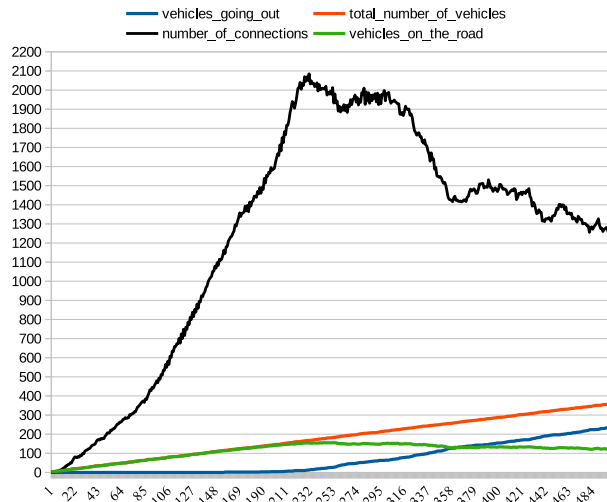


Fig. 4. Evolution of the number of vehicles in the simulation

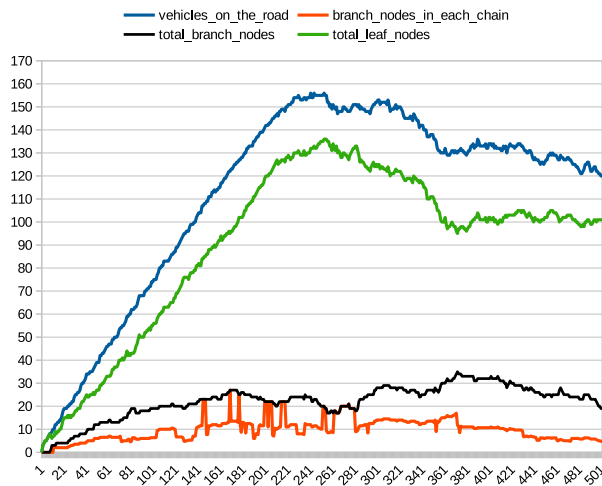


Fig. 5. Evolution of the number of branch and leaf nodes in the simulation

All the models were developed using VLE, a DEVS-based multi-modeling tool that allows creating coupled models. Except the “vehicle” model which will be modified according to the projection of its related model realized with a formal tool, the other models should remain unchanged. Therefore, it is necessary to validate their design and verify that they behave correctly according to the corresponding vehicular network when compared to other specialized and well-established simulation tools. We performed this validation by simulation using the following configuration:

- Network size: the network includes a total of 358 vehicles on the A27 highway in France. The trajectory data have been generated based on real-world traffic data of the A27.

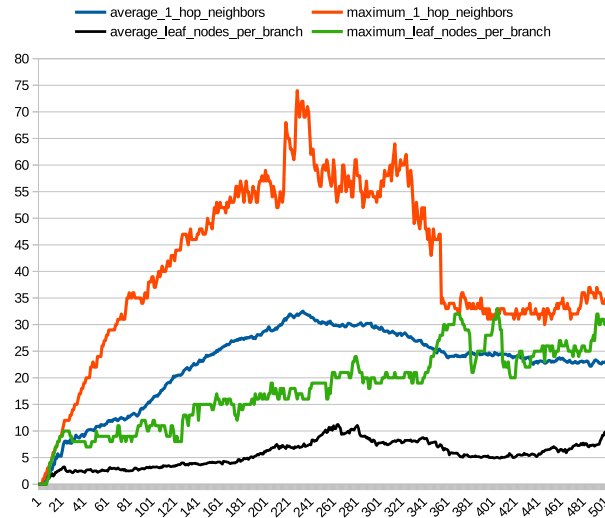


Fig. 6. The number of one-hop neighbors and leaf nodes per branch in the simulation

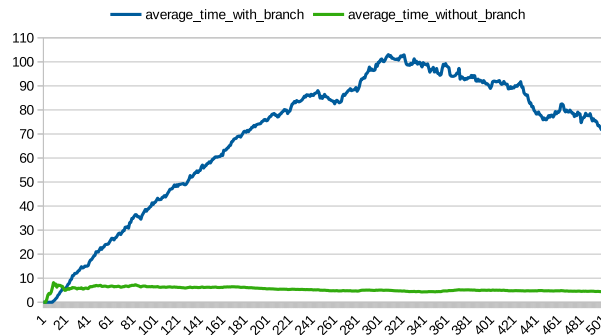


Fig. 7. The duration a leaf is attached or not to a branch in the simulation

- Mobility: each vehicle is associated with one of the available trajectories. The trajectory determines the entry date of the vehicle on the road, its movement realized by successive segments with heterogeneous constant speeds (segments of different lengths and different speeds respectively) and its exit date from the road section.
- The OLSR protocol operates according to referenced settings¹⁸. For the moment, only the sending and receiving of HELLO messages required by the CBL scheme are modeled. The communication range is fixed to 500 m.

Figure 4 shows the number of vehicles entering to the simulation, the number of vehicles leaving the simulation and the number of vehicles simultaneously present in the road section. We also see the total number of active connections at each observation step. The highest value is reached when the maximum number of simultaneous vehicles is reached (155), then it decreases and stabilizes around 1300 when the number of vehicles stabilizes itself about 130. The total number of branch nodes is 15% up to 35% of the total number of nodes (Figure 5). Therefore about 70% of the vehicles are leaf nodes and do not retransmit broadcast traffic, which confirms CBL performance results¹⁸. The number of branch nodes per chain indicates that there are 1 to 2 connected subsets in each traffic direction, which confirms that the vehicular network is entirely connected, at least in the same traffic direction. Figure 6 shows that each vehicle has an average of 80 neighbors in the entire VANET, thus 40 in the same traffic direction. Those which are branch nodes are selected by 20% to 40% of their neighbors which attach as leaf nodes. Each of these leaf nodes remains attached to a branch node 90% of the time (Figure 7), and a node remains without any branch less than 10% of the time. This demonstrates that isolated nodes remains only few time out of the vehicular network. All these results

show that these DEVS-based models of a VANET implemented using VLE allow obtaining the same performance for OLSR with the CBL scheme than those obtained with well-established tools such as MATLAB and OPNET¹⁸. In addition to the testings on each component, these additional results contribute to validate the designed models.

Conclusion

This paper presented a new approach in development which consists in projecting a set of formal models and proven properties on these models through formal tools, in a DEVS-based multi-modeling. Our goal is to put in interaction all these formal models with DEVS models of other components not prone to formal modeling in order to perform the evaluation of the global transport system in a single simulation process. This will allow verifying, by simulation, that proven properties on formal models that might not be sufficiently refined, are not contradicted in certain scenarios. It would also allow producing the results of the simulation as data that could be used in an interactive formal proving loop instead of a human expert. This paper presents the DEVS-based models already realized of an ad hoc network using the OLSR routing protocol and the CBL clustering scheme. These models will be used for the development and the proof of concept of the approach we are developing. These models were implemented using VLE, and validated through a scenario of an ad hoc vehicular network built based on actual real-world traffic data on the A27 highway in France. Future work will concern the design of a formal model of OLSR implementing the CBL scheme in Event-B.

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