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Technical report 04-017

A test bed for multi-agent control systems in road traffic management*

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If you want to cite this report, please use the following reference instead:
R.T. van Katwijk, P. van Koningsbruggen, B. De Schutter, and J. Hellendoorn, "A test bed for multi-agent control systems in road traffic management," *Proceedings of the 8th TRAIL Congress 2004 – A World of Transport, Infrastructure and Logistics – Selected Papers* (P.H.L. Bovy, ed.), Rotterdam, The Netherlands, pp. 309–329, Nov. 2004.

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A test bed for multi-agent control systems in road traffic management

TRAIL Research School, Delft, November 2004

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Abstract

As the complexity of traffic control on a network grows it becomes more difficult to coordinate the actions of the large number of traffic management instruments that are available in the network. One way of handling this complexity is to divide the coordination problem into smaller coherent subproblems that can be solved with a minimum of interaction. The decomposition of a problem into various subproblems is an active field of research in the world of distributed artificial intelligence. In this paper we present a test bed for multi-agent control systems in traffic management. In literature no consensus exists about the best configuration of the traffic managing multi-agent system and how the activities of the agents should be coordinated. The system should be capable of managing different levels of complexity, a diversity of policy goals, and different forms of traffic problems. The test bed presented here aids in-depth research in this field.

Keywords

Traffic management, multi-agent systems, distributed traffic control, test bed, traffic intersection control

1 Introduction

The current traffic situation results from the superposition of many events, both foreseen and unforeseen. In traffic management one therefore has to balance between control and contingency:

1. The control part deals with the redistribution of network traffic flows in order to prepare for foreseen traffic situations. The weather condition, morning and evening rush hour, planned road works, and bridge openings are events that can be foreseen and that can be prepared for. Given the foreseen available network capacity and traffic demand the road network can be tuned using the available traffic control instruments which can be instructed to influence the road-user's route preference, to adjust the current speed limit, to reduce the inflow of on-ramp traffic to the mainline, etc.

2. The contingency part deals with events that are difficult to foresee, such as minor accidents or incidents, a truck that is loading on the street, a vehicle that fails to start at a traffic light etc. It is intractable for a traffic operator to prepare for and respond to all these minor disturbances even if he is supported with advanced decision support systems. This is largely due to the complexity of the control instruments and the speed with which the operator should respond to these disturbances.

One way to more effectively handle contingencies is to make the traffic control instruments more intelligent and have them deal with the intricacies of configuring the traffic control instrument to the situation at hand. The traffic operator can then focus on the direction of traffic over the network, since a part of the problem is dealt with by the traffic control instruments. This delegation of tasks into various sub tasks is an active field of research in the world of distributed artificial intelligence. Choy et al. (2003); Ferreira et al. (2001); Findler et al. (1995); Irani & Leung (1996); Kosonen (2003); Lei & Özgümer (2001); Liu & Gong (2003); van Katwijk & van Koningsbruggen (2002) argue that multi-agent systems can aid in the distribution of the problem and facilitate the coordination of the activities of the traffic control instruments when needed.

We present a test bed for multi-agent control systems in road traffic management. In the literature no consensus exists about the best configuration of the traffic managing multi-agent system and how the activities of the agents that comprise the multi-agent system should be coordinated. The system should be capable of managing different levels of complexity, a diversity of policy goals, and different forms of traffic problems.

To be able to experiment with different strategies for the application of multi-agent systems for dynamic traffic management and to examine their applicability we need a test bed. Such a test bed facilitates the development of multi-agent systems for dynamic traffic management. The main requirements of the test bed are that

1. The traffic managing multi-agent system can be configured easily.

2. The business logic of traffic engineers can be easily implemented, if possible by the traffic engineers themselves.

3. The traffic managing multi-agent system can be evaluated in a realistic simulated traffic environment.

4. The traffic managing multi-agent system can be easily transfered to a real-world application

This paper presents a test bed that satisfies the above requirements, and is organized as follows. In Section 2 an overview is given of current, different approaches to decentralized traffic control. The test bed is described in Section 3. An example application is described in Section 4. We conclude this paper in Section 5 with our future research.

2 Decentralized traffic control concepts

In the literature many examples exist where the answer to the dynamic traffic control problem is sought in the form of a traffic control center that monitors the traffic network and performs a global, or network-wide, optimization to set up new parameters for its local controllers. Much of this work has focused on centralized, and typically predictive, control. Although this approach is very appealing it just is not always possible to do this efficiently and effectively, which is largely due to amount of data involved and the computational complexity of the problem.

Therefore, a partial solution to network-wide traffic control is sought in problem distribution or decentralization. This section discusses the different approaches taken to traffic controller coordination in decentralized control In the literature. We look at *hierarchical controller coordination*, *inter-controller coordination* and *intra-controller coordination*.

2.1 Hierarchical controller coordination

In order to maintain a network manager's overall control objective, given that part of the control is delegated to local controllers, many authors make use of a hierarchical structure in which higher-level agents are able to monitor lower-level agents and are able to intervene when necessary. An example of such a structure is given in Figure 1.

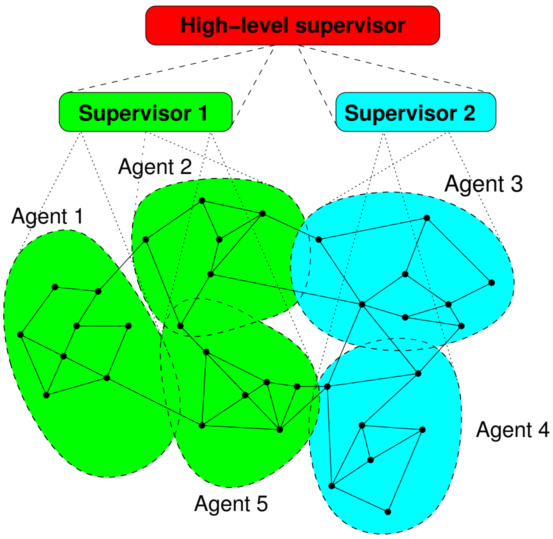


Figure 1: Schematic representation of hierarchical controller coordination

In *SCOOT* Hunt et al. (1981), *OPAC-VFC* Gartner (1983); Gartner et al. (1999), and *MOTION* traffic controllers are centrally coordinated. A traffic model is used to adapt the cycle time and the offsets of the intersection controllers.

In *TRYS* Hernández et al. (1999) so-called 'problem areas' are defined in a particular traffic situation. Each problem area has an agent assigned to it. The agents formulate actions to be performed and propose them to a 'coordinator', who makes a final decision in case of conflicting plans. Choy et al. (2003) introduce middle-level zone controller agents and highest-level region controller agents to coordinate the actions of the intersection controller agents that are present at the lowest level. In both of these approaches there is no communication between agents at the same hierarchical level.

In the *SCATS* model the network is subdivided into regions with homogeneous flow characteristics. Coordination is achieved through communication that takes place on the same hierarchical level. Coordination between regions takes place through the adoption of a common cycle time. Coordination within a region takes place through the change of the offsets.

In *SPOT* Mauro & Taranto (1989), and *PRODYN* Henry et al. (1983) the individual intersection controller are implicitly coordinated through the exchange of forecasted traffic outputs. The controller actions are not explicitly coordinated. SPOT-controllers can be coordinated on a network level through use of UTOPIA.

2.2 Inter-controller coordination

Many applications of intelligent agents in dynamic traffic control aim to make the local controllers more intelligent. The added intelligence aims to make the local controller more susceptible to the interest of the network as a whole. In principle, a local controller works on the basis of local information and can therefore perform only local optimization. In the literature many different approaches are taken to overcome this shortcoming. The most common approach is to share information among controllers (see also section 2.1). Another approach is to make the road infrastructure responsible for controller coordination.

The advantage of using an infrastructure-centric approach instead of a controller-centric approach is the fact that the former abstracts more easily to the network control objectives used at a higher level. When capacity is a constraint, a traffic operator needs to decide which traffic streams and thus which infrastructure must be given priority to. When making the road-infrastructure responsible for controller-coordination, it can be left to the road-infrastructure to come up with a new signal plan. This is the approach we take in van Katwijk & van Koningsbruggen (2002).

In most cases information is only shared upstream. In fewer cases Ferreira et al. (2001); Findler et al. (1995); Lei & Özgümer (2001) this information is also shared downstream. The sharing of information can be done on the level of:

- operational information (often raw detector data),
- tactical information (processed, derived data), and
- strategic information (planned, future, control actions).

2.3 Intra-controller coordination

The task of controlling a single, isolated intersection is often perceived to be one, undividable, centralized control problem, but numerous examples exist in which the control of a single intersection is stated as the result of a negotiation process between multiple intelligent agents, each having their own control objective. These agents can either represent the individual signal groups Irani & Leung (1996); Kosonen (2003), phases Liu & Gong (2003) or the arms of the intersection.

To date, no literature can be found that compares the merits and downsides of each of the chosen approaches to traffic controller coordination. The test bed will enable us to make this comparison.

3 Components of the test bed

This section discusses how the test bed is set up. In traffic control two processes can be distinguished. First of all, there is the *traffic process*. This process can be observed by means of monitoring equipment (e.g. induction loop detectors, floating-car data) and influenced by traffic control instruments (e.g. variable message signs, ramp metering installations, traffic signals), which form the working material for the traffic control process. The second process, viz. the *control process*, is, in the case of our test bed, comprised of multiple interacting intelligent agents.

The test bed consists of an *interaction model*, *intelligence models*, and a *world model*. These models are presented in the next subsections. Figure 2 shows the relations between these models. For a more detailed discussion of the material, we refer to van den Bosch & Menken (2003).

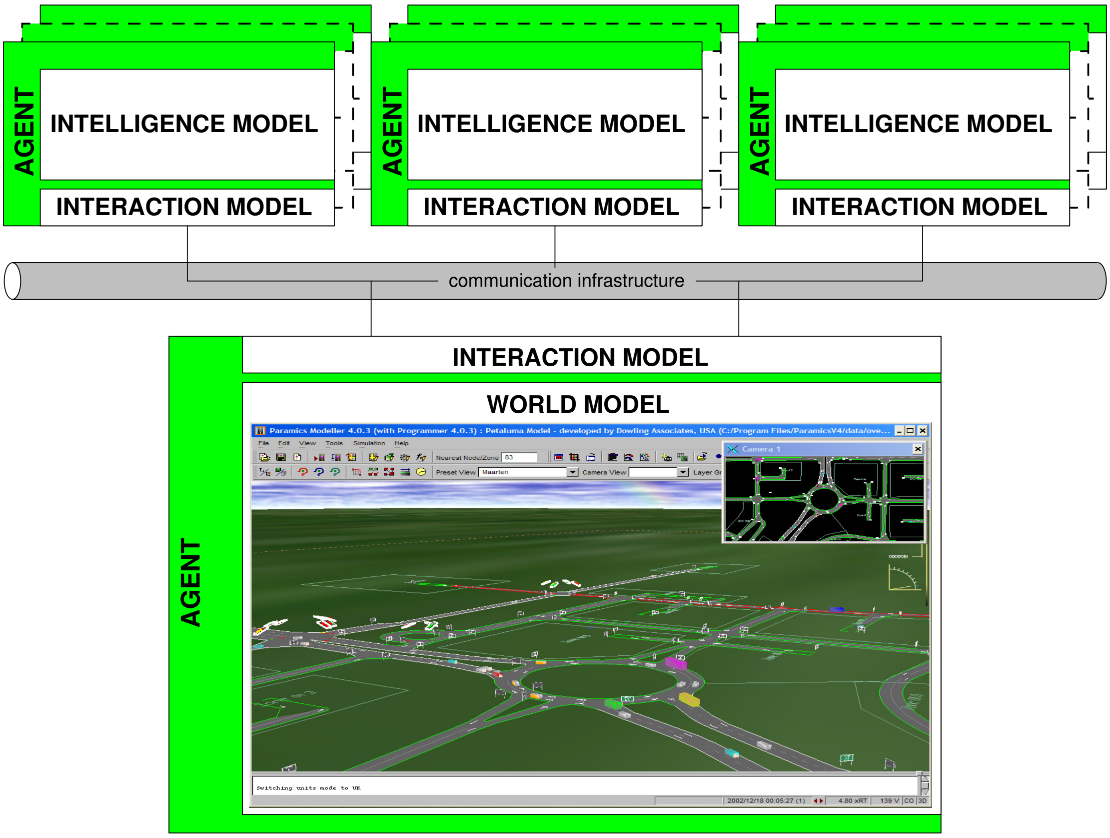
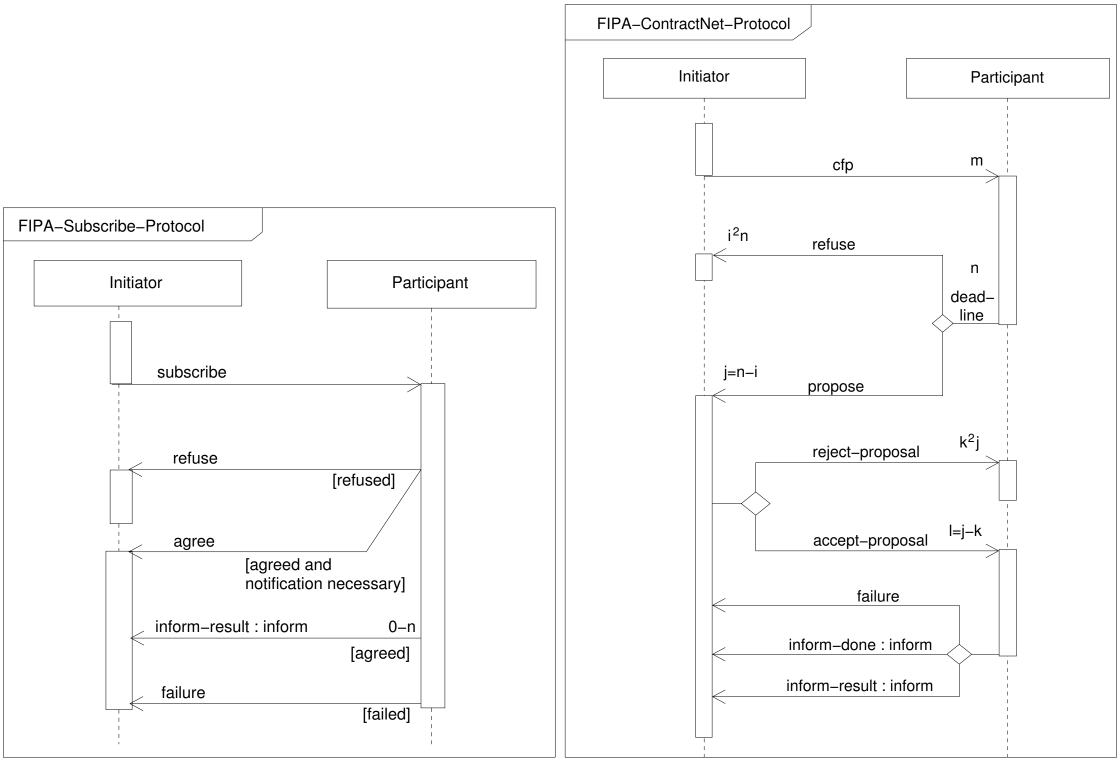


Figure 2: Overview of the components of the test bed

3.1 Interaction model

The interaction model is used to model the interactions between the agents. All communications in our test bed conform to the specifications as set by the Foundation for Intelligent Physical Agents (FIPA) FIPA (2003), an approach also taken by Botelho (2000) for a video-based traffic monitoring system. The core message of FIPA is that through a combination of speech acts, predicate logic and public ontologies, standard ways can be offered of interpreting communication between agents in a way that respects the intended meaning of the communication. Ontologies provide the vocabulary



(a) FIPA subscription interaction protocol (b) FIPA contract net interaction protocol

Figure 3: FIPA interaction protocols

for representing and communicating knowledge about a topic and a set of relationships and properties that hold for the entities denoted by that vocabulary.

The FIPA standards require that each agent publishes the services it provides to a directory facilitator. This directory facilitator is a component of the multi-agent system that provides a yellow-pages directory service to agents. At least one directory facilitator must be present in the multi-agent system. The presence of a directory facilitator enables a dynamic configuration of the agent system. This way the location of a service an agent needs for its own operation does not have to be hard coded in the agent, but can be found at run-time though means of the directory facilitator.

FIPA's standard interaction protocols and communicative acts are currently sufficient for our purposes. Examples of these are the subscription interaction protocol (Figure 3(a)), contract net interaction protocol (Figure 3(b)) (for negotiations), the propose interaction protocol and the request interaction protocol, all of which we need for our cooperating traffic agents. For this we rely on the JADE agent development environment Bellifemine et al. (2002).

3.2 Intelligence model

The intelligence models are used to model an agent's intelligence. A fundamental decision in defining a problem is deciding how to model it. The dynamic traffic management domain has always been open to unconventional approaches from the field of artificial intelligence, including evolutionary algorithms, knowledge-based systems, neural networks and multi-agent systems Cuena et al. (1995); Krause & von Altrock (1997); Molina et al. (1998); Ritchie (1990); Sadek et al. (1999); Taale (2000); Zhang & Ritchie

Table 1: Rule-based intelligence

Business rule
If there is a route named *?route* that has an alternative named *?route-alt* for which the quality of traffic flow is higher **Then** direct traffic from the former route to the latter route using the following message ....
JESS rule

```
(defrule take-action
   (RouteAlternative
      (route ?route)
      (alternative ?route_alt))
   (Route
      (name ?route)
      (quality ?quality))
   (Route
      (name ?route_alt)
      (quality ?quality_alt&:
          (> ?quality_alt ?quality))
=>
   (assert
   (VMSSignal
     (text
       "Congestion on route" ?route
       "Please take alternative" ?route_alt)))
)
```

(1994). Sometimes experience is available to aid in choosing the best paradigm. Often a paradigm is selected on the basis of the applicant's familiarity with it. This is why conventional programming paradigms are often considered first. The test bed we have designed allows programming the intelligence model using a conventional programming paradigm using the C(++) and Java languages, but is not limited to these languages.

Currently the test bed supports the following approaches:

1. *Rule-based inference*
   For our test bed we have developed a generic rule-based agent using *JESS*, a rule-based reasoning engine Friedman-Hill (2003). Incoming messages are converted to facts and asserted into its working memory. Derived facts describing messages to be sent are translated into corresponding FIPA messages, after which JADE takes care of their delivery. The rule-based agent is typically used to program the expertise of a human expert and is as such an ideal prototyping and training tool for traffic managers. Decision rules in an expert system take the form of simple IF-THEN statements. A simplified example of an IF-THEN statement as used for network traffic management is given in Table 1.

2. *Bayesian inference*

For our test bed we have developed a generic Bayes agent using *JavaBayes*, a set of tools for the creation and manipulation of Bayesian networks Cozman (2003). Bayesian inference is a form of statistical inference in which probabilities express degrees of belief. Bayesian inference involves the collection of evidence pointing towards or away from a given hypothesis (e.g. regarding the current traffic state). There can never be certainty, but as evidence accumulates, the degree of belief in a hypothesis changes. Traffic control is guided by uncertainties, namely uncertainties regarding the current traffic state (due to limits in the amount and quality of the available monitoring data), uncertainties regarding the progression of the current traffic state (due to limits in traffic forecasting models), and uncertainties about the effects of a control action on traffic flow.

Incoming messages are converted and assigned to variables in the network. The set of variables that has assigned values is called evidence. The resulting expectations corresponding to messages to be sent are translated into corresponding FIPA messages, after which JADE takes care of their delivery.

3.3 Virtual world

We use the microscopic traffic simulation package *Paramics* developed by Quadstone as our traffic model. Paramics simulates traffic at the level of individual vehicles. Our prime motivation for choosing for Paramics for our test bed is that it can be programmatically extended through an application programming interface. Paramics was one of the first models providing this capability. The test bed can however easily be modified to also use other traffic models that provide a suitable application programming interface. By means of a user-defined plugin, information can be retrieved from the simulation environment for use by the agent-controllers and control actions can be sent back. Traffic simulation models often employ a time-step based method to simulation as opposed to a discrete event based method. Paramics is no exception. It is possible to retrieve detector date and modify the actuators in-between these time steps, which is shown schematically in Figure 4. The agents in a multi-agent system in contrast operate in continuous time. In order to bridge this gap, the Paramics-World Interaction Agent stores the request and subscriptions from other agents until it is time to continue to the next time step. The decision to go to the next time step depends on the type of synchronization one wishes to apply. Since the traffic system is simulated using a single simulation process, there is only *one* agent that handles *all* outside world requests and subscriptions. In the real world each detector and actuator could in principle be represented in the multi-agent system by a specific agent. This is however a theoretical deployment scenario, which will be difficult to attain in practice. Traffic control centers are often equipped with different control applications, each representing a group of detectors or actuators from one manufacturer. A more realistic deployment scenario is that these applications are retrofitted with an agent wrapper (i.e. a piece of code that acts as an interface between the original application and other agents).

Simulation is used to test various real-world application scenarios for multi-agent systems. In order to test whether the configured multi-agent system will function under real-time conditions synchronization can be performed by slowing down the simulation such that simulation time equals wall-clock time. However, the test bed will typically be used to test the performance of a configured multi-agent system with regard to traffic flow. In that case it is required that the multi-agent system gets sufficient time to

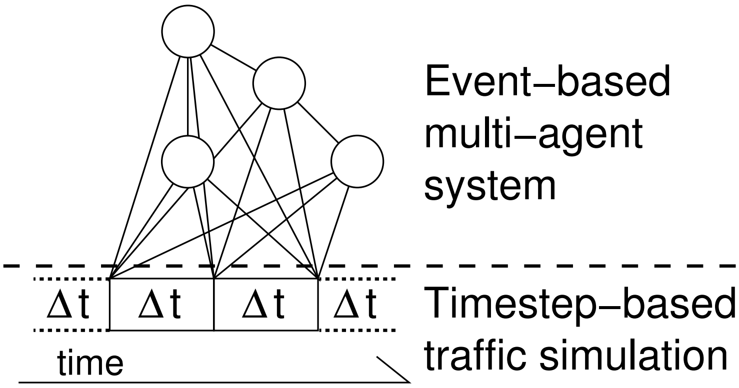


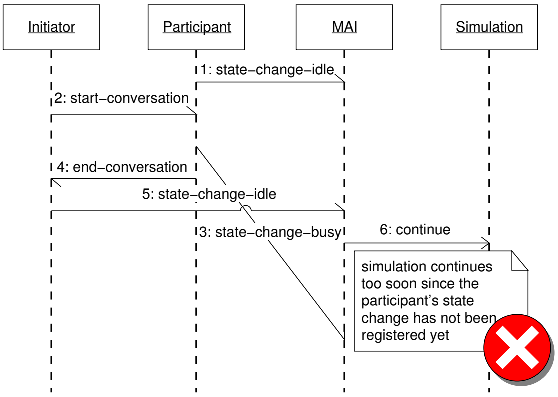
Figure 4: Interaction in discretized time

formulate the control actions and that the simulations are repeatable.

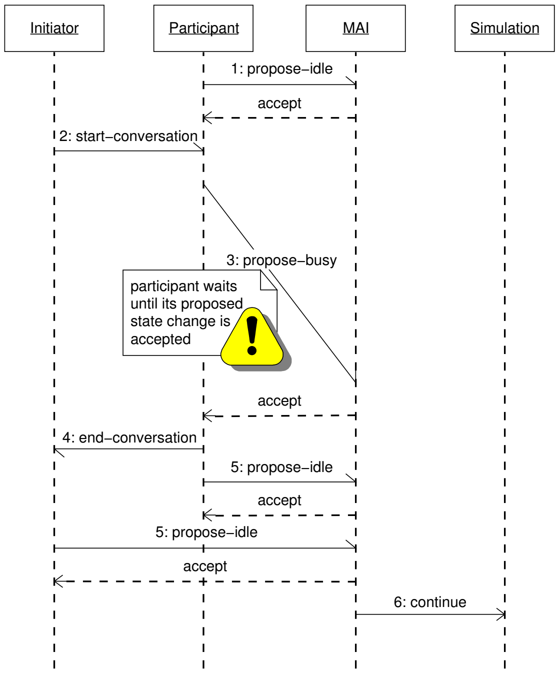
In order to guarantee that the multi-agent system is given sufficient time to formulate the control actions, it has to be determined when the agents in the multi-agent system have finished formulating their control actions. This is done using a special purpose agent, that, when present, requires an agent to report when it wants to change its state from busy to idle. This special purpose agent is named MAI, short for Maintainer of Agent Information. When all agents have reported to be idle, and thus all information on the basis of which control actions can be formulated has been processed by the multi-agent system, the simulation is allowed to continue.

The FIPA propose interaction protocol is used to convey an intended state change from an agent to the MAI. This protocol mandates that proposals are explicitly accepted or refused. The explicit acceptation is required since there is no way to guarantee that messages from the agents informing about an intended state change arrive in the order they are sent. Without explicit acceptation the simulation can sometimes be allowed to continue before the agents are done formulating their control actions. An example of this is shown in Figure 5(a) where the participant message informing the MAI that it changed its state to busy (at the initiation of the conversation) arrives at a later time than the protocol initiator's message informing the MAI that it has changed its state back to idle (when the conversation has ended). Figure 5(b) shows the same communication trace where each proposed state change is explicitly accepted. In this case it is guaranteed that the simulation continues only when all agents are done formulating their control actions.

When agents are mandated by the MAI to communicate intended state changes, all agents operate following the higher-level state chart as shown in Figure 6. In this figure the busy state is a composite state which encompasses the regular state charts of the agent when it is operating in unsynchronized mode. When an agent is changing state from idle to busy and vice versa, it first enters an intermediate pre-idle or pre-busy state, where it remains until it receives an accept-proposal message from the MAI in reply to the proposed state change.



(a) State changes are not confirmed: Unsuccessful synchronization



(b) State changes are confirmed: Successful synchronization

Figure 5: Synchronization sequences

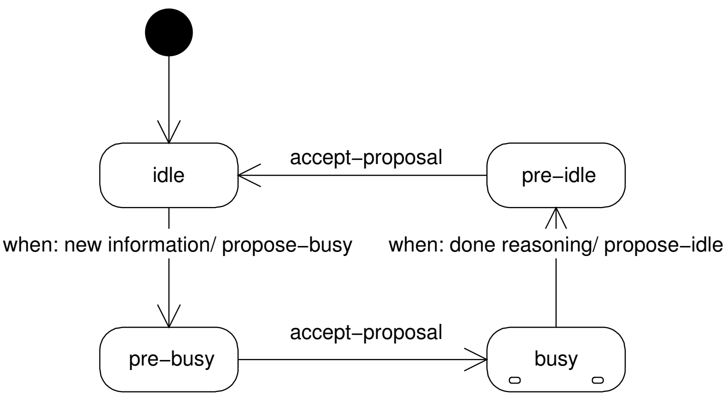


Figure 6: States and transitions needed to ensure synchronized operation

4 An application

Figure 7 encompasses all the approaches to inter- and intra-controller coordination of sections 2.2 and 2.3. Each potentially conflicting interest surrounding an intersection in this figure is represented by a different agent. Each individual signal group (depicted by an encircled s) therefore is represented by an agent as well as each individual entry or exit link.

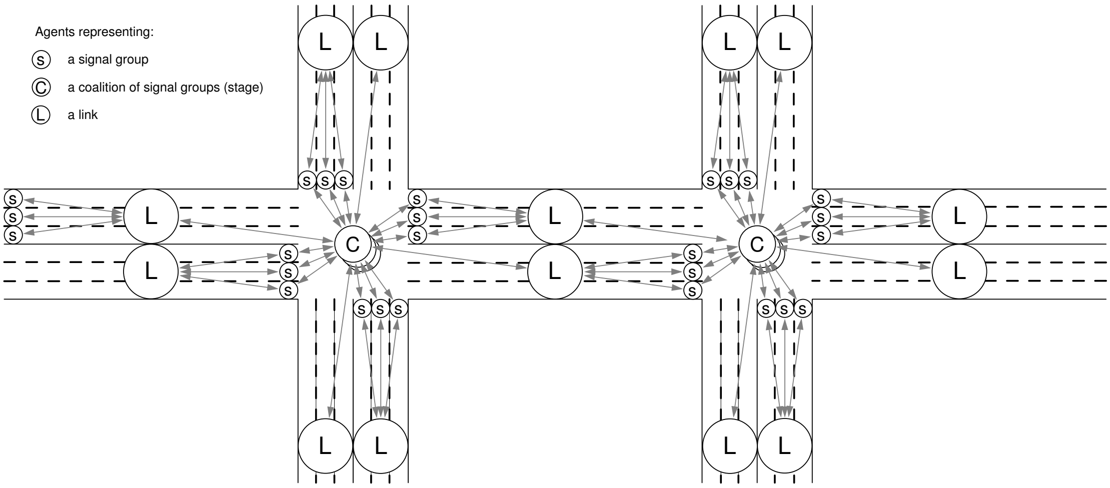


Figure 7: Multi-agent coordinated intersection control

Given this configuration the answer to the question which signal groups get the right to green in the next phase then becomes the result of a negotiation process that takes place among the signal-group agents in which coalitions of signal-group agents are formed. These coalitions consist of signal-group agents that do not conflict with one another, meaning that the signal groups in the coalition can be safely given green simultaneously. The coalitions resulting from the coalition formation process are depicted in the figure as an encircled C. As the coalition formation process is a continuous process, coalitions are constantly formed and dissolved depending on the current traffic demand at the intersection. The strength of a coalition is determined by the combined interests of the individual signal groups the coalition is representing. Coalitions that contain a larger number of signal groups are therefore not necessarily stronger than smaller coalitions.

The coalition formation process roughly corresponds to finding a maximal independent set in a graph Improta (1991), which is a well-known problem in graph theory. When the conflicts between signal groups are represented in a graph G, where the set of vertices V correspond to the signal groups of the intersection and where the edges connect the signal groups that are in conflict with one another, then finding the largest possible coalitions of signal-group agents corresponds to finding all maximal independent sets of vertices (signal-group agents) in that graph. An independent set in a graph is a set of vertices V' such that for every two vertices in V', there is no edge connecting the two, meaning that there is no conflict between the signal-group agents that these two vertices represent.

The maximum independent set problem involves finding the largest maximal independent set in the graph, which corresponds to finding the largest possible coalition, which not necessarily has to be the strongest coalition. The difference lies in the fact that it is not the number of vertices (or signal groups), but the weight of the vertex (or the benefit of given the signal group green) that defines the maximum. Where the opposite of an independent set is called a clique, the opposite of the strongest coalition roughly corresponds to the dominant conflict group, which is determined in the determination of the cycle time when the signal plan of an intersection is determined offline.

The agents representing the signal groups and the resulting coalitions enable us to model the operation of a single, isolated, intersection as a multi-agent system. This enables us to overcome the deficiencies identified by Shelby (2004) of other fully adaptive traffic control algorithms. Even given these deficiencies literature reports substantial benefits of fully adaptive control compared to existing control settings. The lack of a standardized benchmark to compare these algorithms with, makes it difficult to report exactly how much improvement is gained through the use of these algorithms, however delay reductions of up to 30% have been reported by Stallard & Owen (1998). The identified deficiencies are for large part due to concessions made during implementation of these algorithms due to their computational complexity. Since multi-agent systems are naturally distributed the multi-agent approach has a computational edge compared to other fully adaptive control algorithms. On a conceptual level however, when not regarding the computational complexity of these algorithms and when only a single intersection is regarded, the added value of the multi-agent approach compared to these algorithms is limited. This changes however when we introduce the agents that represent the approach and exit links of the intersections.

The agents representing the approach and exit links of the intersection allow us to create a more network aware intersection controller. Entry links forewarn downstream signal groups of incoming traffic, which can lead to the formation of an emergent green wave. Simulation results show that a green wave indeed emerges when the green wave is carrying significantly more vehicles than the crossing directions. The reason for the emergence of the green wave lies in the fact that the directions that constitute the green wave hold the best cards in the negotiation process executed at each intersection.

Our simulation results also show that when traffic is equally spread among all directions of an intersection a green wave almost never emerges. We presume that this is due to the randomness in the arrival process of vehicles approaching the intersection from the north or south. In our future research we will therefore extend the network to a grid network. The randomness of the arrival process can be significantly reduced when the intersections downstream of an intersection are controlled. The exit link agent of an intersection can relate information about the downstream intersection to the upstream signal groups. We estimate that the negotiation taking place between a link and a coalition of upstream signal groups will lead to a “zipper”-like arrival process at an intersection where the “teeth” of the zipper correspond to the platoons of vehicles arriving from the conflicting directions.

5 Conclusions and future research

To aid the ongoing research in the field, we have developed a software environment for rapid development of multi-agent control systems in road-traffic management. In this paper a test bed for agent-based road traffic management is presented. The organization of the software is discussed, as well as the research we are conducting using the test bed.

The presented test bed will be of great value for developments in traffic management. The compliance to FIPA-standards allows us to easily configure a multi-agent system thanks to the FIPA-required directory facilitator. The compliance to FIPA-standards allows us furthermore to transfer the traffic managing multi-agent system to a real-world application more easily. The rule-based and Bayesian intelligence models allow us to easily model the business logic of the traffic engineers.

However, the developed system still has opportunities for further extension. A graphical user interface can be developed in which agents can be created and the multi-agent system can be configured with only a few mouse clicks. This would further accelerate the implementation of the desired multi-agent system. Extending the number of available intelligence models could be another improvement.

With the test bed, a tool has been developed to study the possibilities of applying multi-agent systems in dynamic traffic management. It proved to be a great starting point for our research in decentralized traffic control.

Acknowledgments

Research funded by the TNO spearhead program ”Sustainable Mobility Intelligent Transport Systems (SUMMITS)”, the TU Delft spearhead program “Transport Research Centre Delft: Towards Reliable Mobility”, and the BSIK project “Towards Sustainable Mobility (TRANSUMO)”.

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