Rules Decomposition for Distributed Context Processing

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Abstract

The modification of context information or distillation of other information from context information is called context processing. In existing context processing solutions, this is often performed by the application of rules in a rule engine, running on a centralized server. When working in a distributed environment, this approach is often inefficient, or even unfeasible. Performing rules written for a system as a whole in a distributed environment is often a complex task for the programmers of a system implementation.

This project proposes a method to transform a set of rules written for a system as a whole into a set of rules that distribute functionality in a networked environment. Using the network topology, the capabilities of all system parts in the network and a set of translation rules, it is possible to divide a rule into components distributed over the network.

This method can be automated, allowing it to be used as a tool in the development and management of a distributed context processing environment. Potentially, this task can even be performed in real time in a dynamically changing network.

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Preface

This is the report of the project “Rules Decomposition for Distributed Context Processing” performed for the Twente Institute of Wireless and Mobile Communications. The project has been performed in the context of a masters graduation assignment for the University of Twente, Faculty of Electrical Engineering, Mathematics and Computer Science.

The work reported in this thesis is related to the Freeband AWARENESS project (http://awareness.freeband.nl) in which the University of Twente and TI-WMC participate. Freeband is sponsored by the Dutch government under contract BSIK 03025.

Acknowledgements

I would like to use this space to thank some people who have helped me during this project. First of all I would like to thank the graduation committee, Luís Ferreira Pires, Hartmut Benz and Patricia Dockhorn Costa, for their infinite patience in reviewing version after version of the report, and their continuing support during the slower parts of the project. I would also like to thank my girlfriend Danny Oude Bos for her moral support and tireless reviewing. And lastly I would like to thank my parents and all the other people who have pushed me on to finish this report and the other people that have spent their valuable time reviewing it.

Enschede, July 29th, 2007
Martijn Plass

1 Introduction

This chapter describes the motivation for the project, the objectives, the project approach and the structure of the report.

1.1 Motivation

In Information Technology, one branch of development is that of context-aware computing. Context-aware applications change the way they work depending on their users' context. Context-aware computing allows the application to react to the environment so that what it does is more suited to the user. For instance, context-aware computing allows a cell phone to decide not to sound its ring tone in a cinema while the movie is being shown. Context is gathered from different sources like sensors, personal databases and other devices, and subsequently processed and used by an application.

Context processing is the act of manipulating context information before delivering it to the application. This processing can take several different forms. For instance, each type of context source tends to have its own data format, which usually differs from the application's format. This means that if an application wants to use data from a context source that uses a different format, the data must be translated to the appropriate format. An example of this could be the translation of a GPS location to a street address, or the downscaling of the resolution of a video feed. Another form of processing is the distillation of higher order context information by combining lower order context information from multiple sources. For example, by combining a work schedule and the known location of a user, we might be able to conclude whether or not the user is in a meeting.

A common approach to designing and building context-aware applications is to apply rule-based systems [13,1,14,5,10,15]. Rules are designed to describe the behaviour that the system should have, by describing actions and under what conditions those actions should be performed. The rules are then executed by a rule engine in the application. The advantage of this approach is that the rules can be designed without in-depth knowledge of the system and they can be changed after implementation without having to make changes to the application. There are commercially available rule engine solutions that can handle very complex rules. Some examples are mentioned in section 1.2.

Systems that are developed using the rule-driven approach usually take a centralized form: Because everything revolves around the rule engine, the rules run on a centralized device (Figure 1). Such systems are fairly straightforward to implement and therefore often used. However, systems are frequently not a single device, but consist of lots of different devices connected by a network.

Development becomes more complex when the system is a distributed network instead of a single server. The functionality has to be divided among the devices in the network, which is usually a task for the programmers. If the network is large and a lot of devices have to co-operate, this task can become very complicated. That is why large distributed systems are sometimes handled as a centralized server architecture, where all the distributed capabilities of the devices in the network are ignored and a single device does all the processing, even though that may be far from ideal.

If rules that are written for an abstract system can be automatically translated into rules for a concrete, distributed system, this could potentially allow distributed systems to be designed without a large increase in complexity. This project looks at a way to define a method of breaking up a rule into individual components that can be assigned to devices in a distributed system. If this process can be formally defined, it can then be automated.

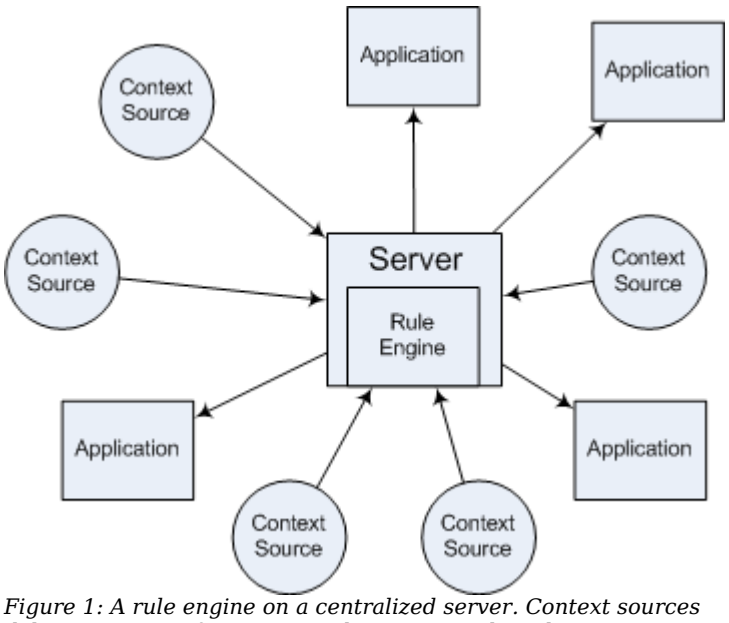


Figure 1: A rule engine on a centralized server. Context sources deliver context information to the Server and Applications receive context information from the Server.

Systems that could benefit from this approach include:

- Sensor networks and systems that incorporate sensor networks.
- Single purpose Ad Hoc networks such as emergency services, military applications, single-type device networks such as printers or alarm systems.
- Distributed computing applications.

In general, any distributed application that runs on a large distributed network could benefit from our approach.

1.2 State-of-the-Art

The practice of describing what systems should do in the form of rules has been around for a long time. Companies designed business rules that describe their policies and employee tasks. When those businesses became automated, the business rules were used to design the system. One of the problems was that policies change very often, which in the case of automation requires reprogramming computers and applications. To avoid this, the first rule engines were developed. They allowed computers to adhere to the business rules and could be easily changed to suit a new situation.

Currently, business rules are still used by companies to define policies and it is a common approach to use a rule engine in a business application or framework [1, 14, 5, 10, 15]. There are not many general purpose rule engines, mostly because they are so complex. A lot of projects use their own, proprietary rule engine that has functionality tailored to the needs of the project.

The commercial general purpose rule engines that are in use today, such as Jess [9], Mandarax [11], Jena [8], Arete [3] and others, all work according to the centralized server approach. They all allow very complicated and expressive rules, but cannot handle a distributed environment. Integrating them into a distributed network would be the job of the programmers implementing the system.

There is a distributed version of Jess, called Djess [7], which allows rule engines running on different devices to share rules and facts in working memory. There is a central manager that keeps track of who is in the group of sharing rule engines. In this approach, the rule engines are distributed, but the rule management and the rules themselves are still the same as in a monolithic approach. Practically speaking, this is another way of forcing a distributed system to work like a monolithic system, although it is a much more elegant way than used in other solutions.

Sørensen et al. describe a context-aware middleware for Ad Hoc Environments [14]. It allows rule engines running on autonomous devices to exchange context data using a publish-subscribe model. Potentially it can be a good basis on which to build a context-aware distributed application, but it requires the rules for the rule engines on the devices to be written and entered manually. For this project, we are looking for a way to generate those rules automatically.

The project “Code Blue” handles a situation very similar to the third scenario that we define in our project, which is an emergency situation involving medical personnel. “Code Blue” is currently under development [6]. The main difference with our scenario is that we focus on the dynamic nature of the network, while in Code Blue the network is considered to be static; nodes may move around, but devices will not leave or join the network.

1.3 Objectives

The objectives pursued in this project have been:

- To formally define a method to translate a rule written for a high level abstract system into rules for a distributed network.
- To design and implement a framework that supports distributed context processing by allowing decomposition and distribution of application rules.

The framework consists of a middleware and a prototype application that uses this middleware. The middleware handles the decomposition and appropriate distribution and forwarding of application rules.

For the prototype application we looked at the first of the three scenarios defined in this project, which consists of a detection system for a ward for patients with dementia (see section 2.1). The prototype is simplified version of such a system.

1.4 Approach

The approach used to reach the objectives is as follows:

- Three scenarios are defined that are used as a basis in this project. These scenarios supply the requirements for the middleware.
- Existing solutions for context aware applications in a distributed environment are examined, with solutions using rule engines in particular.
- A method for rules distribution is designed and described, followed by a formal definition of this method.
- The rules distribution method is applied to the three scenarios: Requirements from the scenarios are used to write rules and the effects of rules distribution on the scenario are defined.
- The prototypes are implemented. There are two prototypes, one used as a proof of concept and as a preparation for the second, more complex prototype that illustrates the method for rules distribution.

1.5 Structure of the Report

The structure of this report reflects the project approach:

- Chapter 2 gives a detailed description of the scenarios used in this project.
- Chapter 3 explains how rules can be used to describe the behaviour of a system and how those rules can be adapted and distributed to parts of the system.
- Chapter 4 gives the formal definition of rules decomposition.
- Chapter 5 shows how the rules approach can be applied to the scenarios.
- Chapter 6 describes the prototype implementations.
- Chapter 7 evaluates and discusses the results of the project, in particular the design and the prototypes.

The Glossary on page 55 gives a short explanation of terms used in this report.

2 Scenarios

This chapter discusses the three scenarios that form the basis for the middleware design, the requirements and the prototypes. They describe a sensor network in a home for the elderly, a user walking around in an ad-hoc network and an emergency ad-hoc network being formed at the site of a calamity.

Although these three scenarios describe three very distinct situations, they have a common aspect: in all three situations devices in a network must work together to accomplish a task relevant to the scenario. Looking at the scenarios it is possible to identify overlapping requirements that can lead to generic functionality. These requirements are discussed in Chapter 5.

2.1 Scenario Elderly Home

In Enschede there is an organisation called Livio that runs several large homes for the elderly in the region. These homes are so large that finding people who are lost in the home can take up a lot of time, especially if they are not fully aware of their surroundings which may happen to people suffering from dementia. Livio is looking for new ways to automate security in their wings for demented patients to reduce the amount of patients getting lost in the building complex and to make it easier to find them when they do get lost.

This is an example of how the system might work in practice:

> *Mrs. Smith is a demented resident living in an elderly home. As she walks along the hallways of the ward for demented residents, the system registers her as being in an admissible area. At a certain point in time she attempts to pass the ward's main entranceway, which has been classified as an inadmissible area.*
>
> *As she moves closer to the door, the system registers her as being close to an inadmissible area and starts to track her exact position and that of any caregivers or visitors closeby. When she reaches the door, the system checks if there is a caregiver in her immediate vicinity and when it concludes there is not, the door lock closes.*
>
> *Unfortunately, the door malfunctions and Mrs. Smith succeeds in passing through the entranceway. The system now registers an alarm situation and alerts all caregivers nearby with a message: "Mrs. Smith has entered a restricted area: hallway 104b, first floor, East wing". As the patient moves through the building, the alarm is updated to include the new location.*

In a home for the elderly with a ward for demented patients, it is unwanted but not uncommon for a patient to wander from the ward into another part of the home, or to escape the home and walk off alone outside. Caregivers usually notice that a patient is missing in a timely fashion, but finding where the patient has gone off to can take a lot of effort. Therefore, the Livio administration is looking at systems that make it less likely that patients wander off and can reduce the time that caregivers have to spend on locating patients. This scenario describes a possible application of such a system that is being developed in the Freeband AWARENESS project[4].

In the scenario, a system that helps caregivers detect wandering patients is installed in the home. The Livio administration wants the system to have two features:

1. Tracking people in and around the home and using this tracking information to decide whether a patient has wandered off and to generate an alarm message to caregivers in the ward.

2. Monitoring of the daycare room. Part of the ward is a daycare room, which is a large recreation area where patients walk in and out all day. A caregiver must be present in the daycare room at all times as long as there are patients present. The administration wants an indicator to be visible somewhere in and around the daycare room that shows if it is currently unattended or when the last caregiver leaves the area while patients are still present.

There are five stakeholders of importance for the system (see Figure 2):

1. Patients: elderly people living in the home who have a condition that requires them to be monitored.
2. Caregivers: trained professionals who work in the ward to provide care to the patients.
3. Visitors: family and friends of a patient who visit on a regular basis.
4. Administrators: who maintain the system.
5. The organization: the caregiver's employer and responsible for the patients and the system.

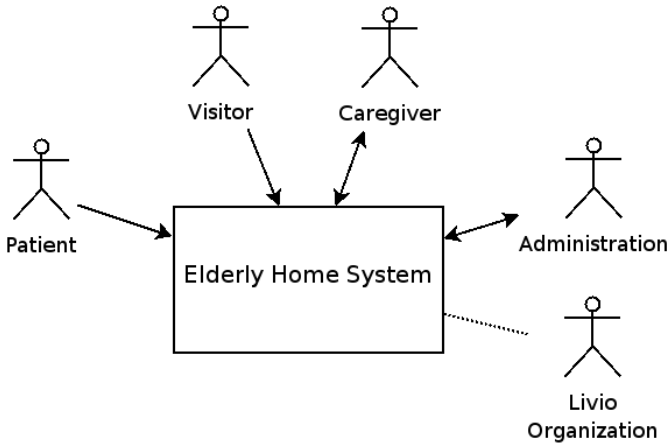


Figure 2: The stakeholders. The patients and visitors only supply information to the system, the caregivers and administration also receive information. The Livio organization is a stakeholder in the system, but has no direct interaction with it.

The home is divided into sections that are admissible to patients and sections that are not. When a patient enters an inadmissible section without being guided by a caregiver or visitor, the caregivers are warned by the system of this event. All areas outside of the home are considered inadmissible.

The main entrance door to the ward is a special location. This door has an electromagnetic locking mechanism, which needs to be turned on when a patient approaches the door from inside without guidance.

2.2 Scenario Task Outsourcing

A user with a portable device in an ad-hoc network encounters a continually changing network environment. Making use of this network despite the changing environment is a challenge, but if done properly it can allow the portable device to outsource computational tasks to other devices.

Here is a example story board of a task being outsourced:

A security guard is doing his rounds in a modern office complex. He has with him a PDA that allows him to watch a selection of realtime video streams from security cameras in his vicinity. The security cameras provide a high resolution, compressed data stream encoded in a format that the PDA cannot use. To display the video data, the data stream must first be converted into a different format. Because the PDA has only limited processing power available, the display drops video frames and shows a low resolution image to keep up with the realtime video stream.

While the security guard is doing his rounds, he comes within range of an access point, with a connection to a static processing server. The task of converting the video streams is transferred to the processing server, and the data from the cameras is directed there as well. At the cost of a slightly longer delay, the PDA can now display the data received from the processing server, resulting in a high resolution image at a higher frame rate.

When the guard leaves the range of the access point, the data stream is cut off, and the PDA resumes its own data processing.

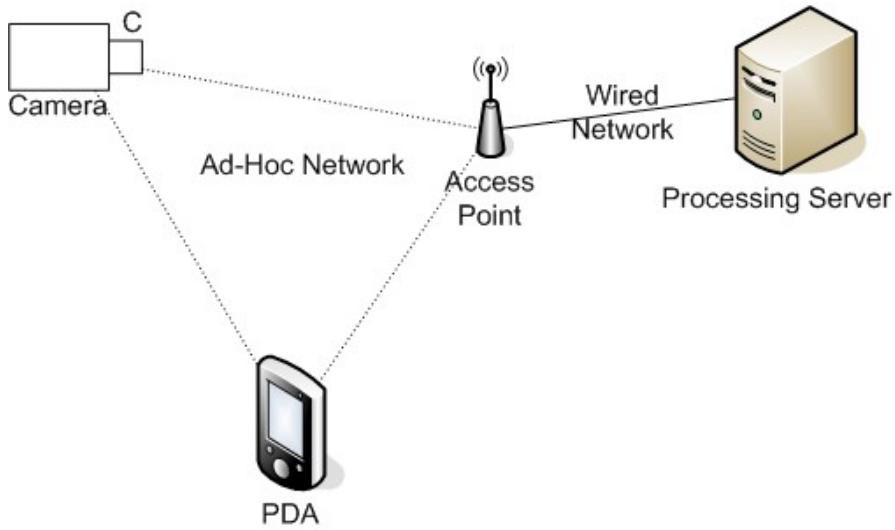


Figure 3: Task Outsourcing example

The example is illustrated in Figure 3. When the security guard's PDA comes within reach of an access point, it has a means of communicating with the processing server. Once the PDA detects that the processing server has spare processing power, it transfers its context processing tasks to the server. The video streams from the cameras are directed through the access point and to the server, where they are converted to the PDA's format. The resulting data is sent back through the access point to the PDA, where it is displayed on the screen.

So, in more general terms, the user is walking in an area covered by an ad-hoc network. One of the user's portable devices is performing tasks, but for whatever reason is not able to perform them optimally. The device inquires on the ad-hoc network about other devices that can help it perform one or more of those tasks, effectively 'outsourcing' the task (illustrated in Figure 4). If the ad-hoc network has access to stable network infrastructure such as the Internet it may try to contact known services for outsourcing. For the purpose of this scenario, we look at context processing as a task that can be outsourced.

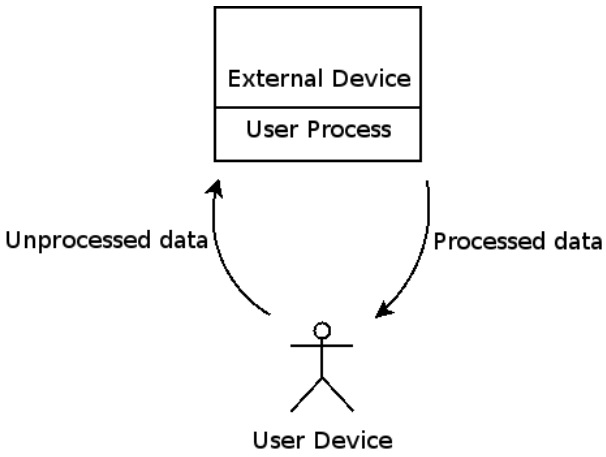


Figure 4: Task outsourcing

An issue that arises in task outsourcing is trust. Can the application trust that the server converts data to the proper format without changing the contents? Can the server trust that the conversion code is safe for use? To allow this sort of distribution to happen, a certain level of trust must be ensured.

2.3 Scenario Emergency Situation

On the site of an emergency situation an ad-hoc network forms amongst the available devices installed in vehicles and carried by personnel. Context processing tasks that are performed by devices with limited resources, can move to a more powerful device as they join the network. This allows more and more costly processing tasks to be performed as the network grows, which results in more and more detailed information. This information can feed medical applications that assist medical personnel in giving aid to patients on the scene.

In reality, the scenario might happen like this:

> *On a busy highway, a large traffic accident has happened with dozens of cars involved. A large amount of ambulances, police cars and fire brigade trucks speed to the scene of the accident. In such a calamity, the first doctors to arrive start to triage patients instead of treating them. They place basic sensor nodes on the casualties that monitor functions like ECG, blood pressure, et cetera. The doctors carry PDAs that can each monitor the output of a few sensors around them. As they move from one triage patient to another, sensor data from the last patient cannot be logged and is lost.*
>
> *Fortunately, when ambulances arrive at the scene, the on-board computers form an ad-hoc network with the PDAs and sensor nodes so that the logging data can be passed on to the more powerful computers. There all data can be stored and analyzed.*
>
> *When enough doctors and paramedics arrive to start treating patients, they can call up the known data about any patient that has been triaged.*

The sensor nodes are cheap disposable units that are used only once. When they are applied to a person, they join the ad-hoc network and start sending out their data. The triage doctors use their PDAs to look at a patient's vital signs and use those signs in their evaluation of how serious the injuries are. The PDAs can store the data of some sensor nodes, but if there is a large number of patients to be triaged, they will run out of space, which means that data is lost.

When ambulances arrive at the scene, their on-board computers join the network. Those computers have more processing power and storage capacity than the PDAs. As soon as they join the network, they evaluate the current situation of the network, spot which sensor nodes are not being logged and start logging the data from a subset of them. Data from sensor nodes is grouped per person they are attached to, so that when the doctors start treating people they have an overview of the stored sensor data to evaluate. It is also possible that easy-to-interpret signals like ECG are automatically monitored, and if the signal indicates a problem such as a heart attack, the sensor immediately informs the doctors carrying a PDA.

When a new resource is introduced in the network, decisions should be made as to which tasks should be moved to this resource. When a task is being moved, it is vital that the stream of processed data is not interrupted or corrupted. PDAs or other mobile devices should be able to evaluate their performance, and come to the conclusion that tasks should be moved when the device will no longer be able to perform them (e.g. when the device moves away from the network or when it is running out of power).

3 Rule Distribution

The main issue of this project is how rules can be used to aid context processing in a distributed environment. In this chapter we discuss a method for doing this.

In section 3.1 we explain the concept of rules. Section 3.2 explains our approach to rule distribution. Section 3.3 explains why the decomposition process can be necessary and how it works. Section 3.4 shows how the decomposition process can be used.

3.1 Rules

In general, *rules* are used in information technology to describe a *cause and effect,* such as for example: “When enough heat is applied to ice, the ice melts”. The cause is a set of events and conditions that describe what state must hold so that the effect can happen.

In our project, we assume that rules are described by an *event*, a *condition* and an *action*. Whenever an event defined in a rule occurs and the condition of the rule is true, the corresponding action is performed. Events are generated by a system and can represent anything that is detected. The condition checks the state of the system. Consider the following example rule for an intelligent lightswitch:

If no-one is in the room for 5 minutes and the light is on, turn off the light.

In this rule, the event is “no-one is in the room for 5 minutes”, which would occur 5 minutes after the last person leaves the room. When this happens, the condition “Is the light on?” is checked. If this condition is true, the action performed is “turn off the light”.

An application rule is a rule that describes a combination of cause and effect that should occur in a system. There can be many applications supplying rules to the system and the set of all application rules together describe the system's behaviour.

Rules can be used in two ways: *during development* of a system to define what functionality the system should have so that it can be implemented, or *at runtime* to introduce or change behaviour in an existing system.

3.2 Approach to Rule Distribution

At the highest level of abstraction, a system is a single entity that interacts with its surroundings. The system's behaviour (or desired behaviour) can be described by a collection of rules that are composed of a set of events, conditions and corresponding actions. These rules are global and monolithic. They are global in the sense that they describe the system behaviour on the highest level and abstracting from the underlying network, and monolithic in the sense that each rule describes a distinct and unique aspect of behaviour.

At a lower abstraction level closer to implementation, systems often consist of a network of devices that have different capabilities (as illustrated in Figure 5). Presenting the rules defined for the abstract system to all the parts of the network does not mean that the system can perform them. They may not have all the functionality required to perform the rules, even though the system as a whole might be able to.

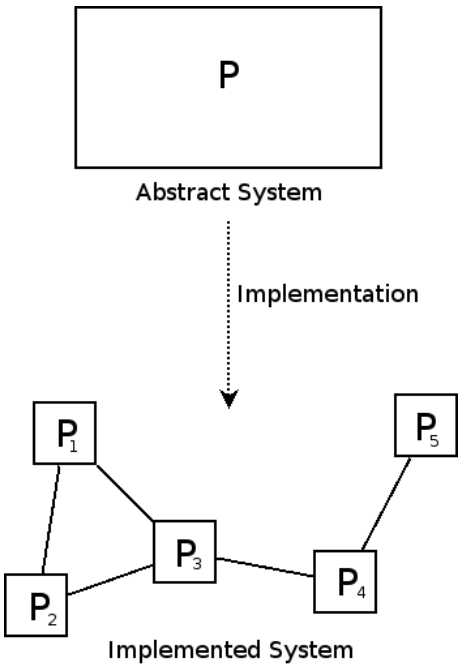


Figure 5: Abstraction Levels

For instance, a rule involving a sensor network may describe the storage of large amounts of sensor data, but a sensor node in the network has only limited capabilities and cannot store the amount of data required. However, there is a database in the network that can. So in order to allow the system to perform the behaviour defined in the rule, several devices in the network have to work together. What this means for the global rules is that they need to be broken down and translated into sub-rules for the different parts of the system before they can be assigned to those parts. This breaking down and translation of rules is performed in such a way that the resulting behaviour of the new set of rules when observed from the outside is the same as the original set of rules. In other words, if both systems are interpreted as a black box, they are indistinguishable. Under these conditions, we call the process of creating the new rule set *decomposition*.

3.3 Rule Decomposition

As we described in section 3.2, it may be possible that rules written for an abstract system are not executable at a lower abstraction level in a distributed system. Rules must be decomposed and distributed over the system parts in order to be executed.

Definition: Rule *decomposition* is the act of transforming a set of high level rules for an abstract system to a new set of lower level rules for a system closer to implementation, so that the lower level ruleset defines the same observable behaviour as the high level rule set.

To illustrate why decomposition may be necessary, we use the example of a (fictitious) shipping company:

> *The shipping company "Jansen" located in the Enschede harbour has a large storage facility and ships cargo by truck from the harbour to anywhere in Europe. The storage facility has autonomous transport robots and a large automated administration system. The network of computers, robots, humans and cargo has become so large that making changes to how the system works is now a very complex and time intensive job. The IT department has recently decided to organize the system so that application rules can be used to describe how the system works.*

The company has the following rule for their automated transport system:

> *When a customer declares that a crate is fragile, then attach a label to it and take extra care in packaging and moving the crate.*

The rule above defines behaviour that the system should adhere to. However, in reality the system consists of a large network of devices with varying functionality; there are powerful computers like web servers that handle orders and servers that handle shipping information, but also autonomous robots that lift crates, truck drivers that require specific route instructions and even simple devices like the coffee machines or fire alarms. None of the parts of this system have all the functionality required to perform this rule, which means that if the shipping company wants the system to execute this behaviour, then the rule has to be decomposed into a more suitable form.

One of the problems to be tackled in this decomposition is that not every system part may understand the concepts used in the rule. A robot picking up crates and putting them on lorries needs to know what 'extra care' means in its context. For the robot it may mean using a different set of grapplers, but for a truck driver it may mean driving only across paved roads. If the system is to use this rule, then the concepts in the rule must be translated to something that the different system parts can understand. Furthermore, the rule as a whole may include things that are irrelevant to parts of the system. For example, the labelling machine that has only one way of attaching labels to a crate does not need to know about 'extra care'. The crate-moving robot may need to know that it should read labels to see which crates require extra care, but it does not need to know anything about how to attach labels to crates and the cafeteria coffee machine has no need to know anything about this rule at all.

If we want to use a rule like the one above in a system, the rule must be decomposed into separate *sub-rules* and translated to the specific concepts relevant to each component of the system.

Rule decomposition can mean that the set of application rules becomes more complex. Suppose there is a second rule in the shipping company:

> *If a crate becomes damaged, inform the customer.*

Inspecting the system, we could conclude that the crate-moving robot has a sensor that can detect damage and that the central administration system can look up who is the owner of a certain crate and send communication messages to people. If we can then find a means for the robot to contact the central administration system, it is possible to decompose the rule into a sub-rule for the crate-moving robot and a sub-rule for the administration system. Both sub-rules can be executed by the system parts and together perform the behaviour that was defined by the original rule, as it can be seen in Figure 6.

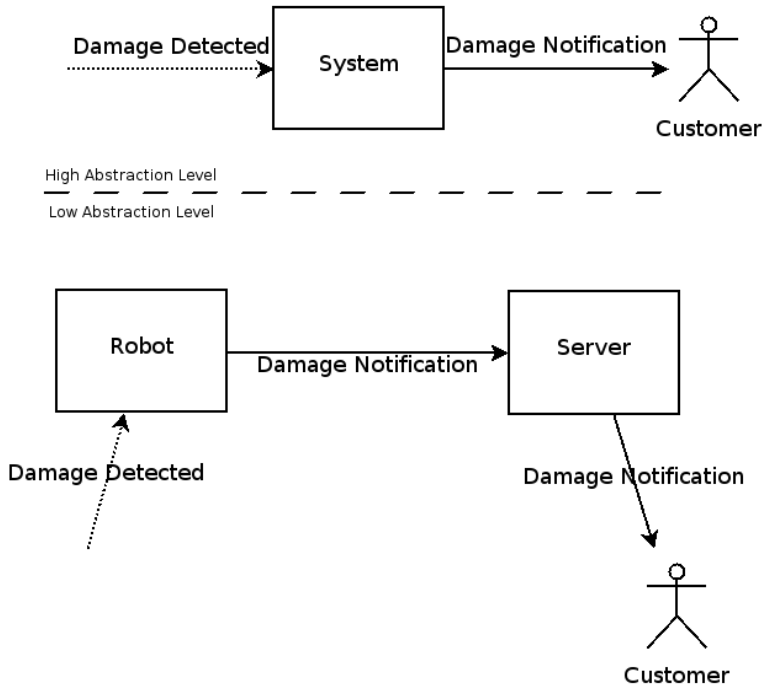


Figure 6: Cooperation between system parts

The examples above illustrate that in order to find the decomposition of a rule we need to look at what capabilities the rule requires, which system parts have these capabilities to offer, and what communication might be required to combine these capabilities into the desired functional behaviour.

3.4 Use of Rule Decomposition

Like we said before in section 3.1, there are two ways in which rules can be used: during development and at runtime. Rule decomposition can also be used in these two ways.

When used *during development*, a general description of what the parts will be able to do is used to decompose the rule (Figure 7). The result consists of several possible decompositions. Each of these decompositions then gives a possible distribution of tasks that, when implemented by the system parts, will execute the behaviour defined by the rule. Which of these decompositions is actually used can be narrowed down further by applying extra requirements to them. The final selection is then made by the system designers or programmers. If there are no possible decompositions, this means the given definition of the system does not have enough functionality to perform the rule.

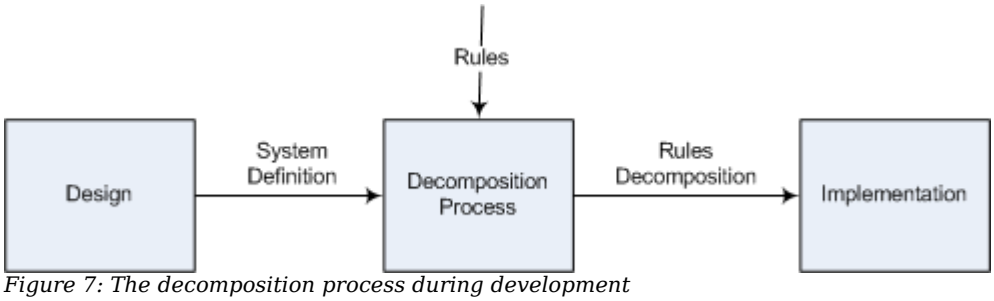


Figure 7: The decomposition process during development

When used *at runtime*, the already existing system parts have precisely defined capabilities and those are used to find a decomposition of the rule (Figure 8). The resulting decompositions give possible ways in which the rule can be executed by the existing system parts, or when there are no possible decompositions this means that the system cannot execute the rule in its current form.

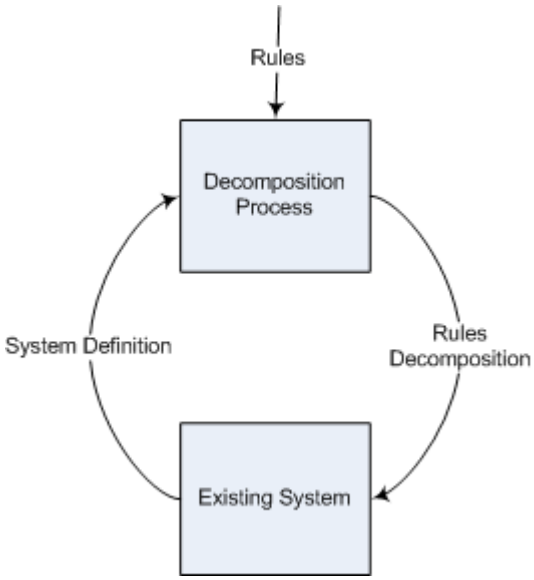


Figure 8: Decomposition at runtime

Because all the capabilities of the system parts are already known, it is possible to fully automate the decomposition and distribution process, potentially allowing it to be performed in *real-time*, as long as the decomposition process does not take too much processing power.

In Figure 9 we identify the input that is needed to perform the decomposition process:

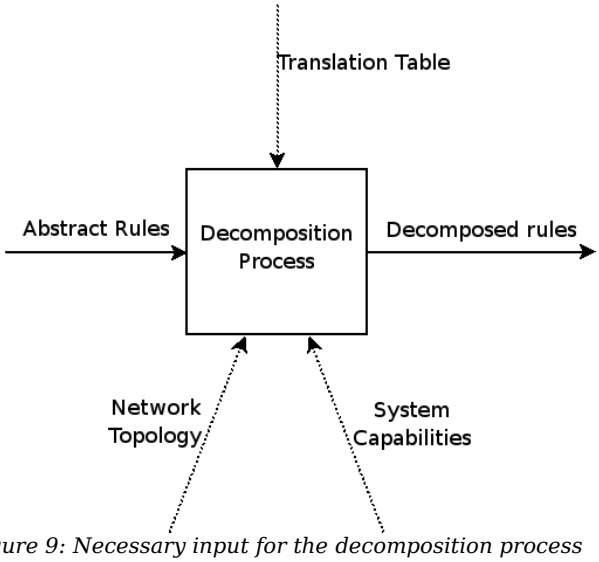


Figure 9: Necessary input for the decomposition process

The network topology is required in order to determine what communication is possible between the network parts. The topology can be automatically constructed, or in the case of development, supplied manually.

We need to know what the parts of the system can do, which sensors it has, which functions it can perform, et cetera. These capabilities are used in the decomposed rules. They can be supplied by the programmer, or each system part may have a way of reporting its capabilities, which would allow this to happen automatically. And finally, we need a way of translating the abstract concepts used in the abstract rules to concepts known to the concrete system parts. Some of these translations are common to most systems, and others will be specific to one system. The common translations can be supplied by a library and the specific translations must be supplied by the programmer.

4 Formal Definitions

This chapter provides the formal definitions for the decomposition process. In section 4.1 we introduce a formal definition of the rule language used in this project. In section 4.2 we give the formal definition of a system and in section 4.3 we formally define the decomposition process.

4.1 Rule Language

In this report we use a rule language to express rules. It uses the Event-Condition-Action format:

Rule: *Event* ● *Condition* → *Action*

In this notation, "●" separates the Event and Condition statements. If the event expression and the condition expression both evaluate to *true*, then the actions are performed.

It is not required that a rule has a condition, i.e. it may be possible that the event itself is enough to trigger an action. In such a case, the condition expression can be a simple *true* statement. Because adding '*true*' to each rule without a condition is not necessary to understand the rule, it can be left out, which simplifies the rule to:

Rule: *Event* → *Action*

The rule for damaged cargo from the shipping company example in section 3.3 can be represented in the rule language as:

R_1: *DamagedCargoDetected(Crate c)* → *InformOwner(c)*

In this rule, c is a variable generated by the event. Variables are explained later in section 4.3.1.

To allow the decomposition process to be automated, it is necessary to formally define it. In addition to the format defined above, we also introduce a formal notation to represent rules.

4.2 System Definition

Before decomposition, we consider an abstract high-level system with its behaviour defined as a set of abstract, high-level rules. In reality, when the system is implemented, it consists of a set of system parts connected by a network, which was illustrated by Figure 5. The implemented system is on a lower *abstraction level* than the abstract system.

We give a formal definition for a system in order to use this definition in the description of the rule decomposition process.

Definition: Any system is a directed graph consistin of a set of system parts L and a set of edges G.

$$System = (L, G)$$

The definitions of these terms are given below:

Definition: The set of system parts L contains the individual system parts that make up the nodes in the communication graph of the system.

$$L \subseteq system\ parts$$

These system parts can be devices, but they can also be networks, groups of devices or types of devices. If a system part is not a device but a network, group or type, the rule set that is assigned to it by the decomposition process can be decomposed further by another iteration of the decomposition process. In the next iteration, this system part becomes the abstract system and the decomposed rule assigned to this system part becomes the abstract rule.

Definition: G is the set of edges. G contains an edge between two nodes if and only if there is a means of direct communication between the corresponding system parts.

$$G \subseteq (L \times L)$$

There is a means of direct communication between two nodes if they can communicate with each other directly through the lower level communication protocol. For example, if two computers are on the same IP network, they have a means of direct communication through the TCP/IP protocol.

Edges can have constraints that include the communication properties and direction. The properties can define the protocol, what sort of data can be sent, how expensive it is to use the communication link, et cetera.

The abstract system in Figure 5 would be defined as $L = \{P\}$ and $G = \{\}$. The implemented system would be defined as $L = \{P_1, P_2, P_3, P_4, P_5\}$ and $G = \{(P_1, P_2), (P_1, P_3), (P_2, P_3), (P_3, P_4), (P_4, P_5)\}$.

4.3 Decomposition Process

We now formally define the decomposition process.

Definition: An abstract rule set $\boldsymbol{R}$ is defined as a set of rules for an abstract system. Each rule in the set consists of terms E, C and A where E is a logical expression containing events, C is a logical expression containing conditions and A a list of actions.

$$\boldsymbol{R} = \{R_n : E \bullet C \rightarrow A\}$$

Consider a situation in which the rule set that holds for the abstract system is not valid for the implemented system because no single system part can execute all the abstract rules. The decomposition process derives a new set of valid rules for each part of the system from the abstract rule set. In Figure 10 we can see how the rule decomposition relates to the implementation of the abstract system. The decomposition process results in a rule R_n for each part P_n in the implemented system.

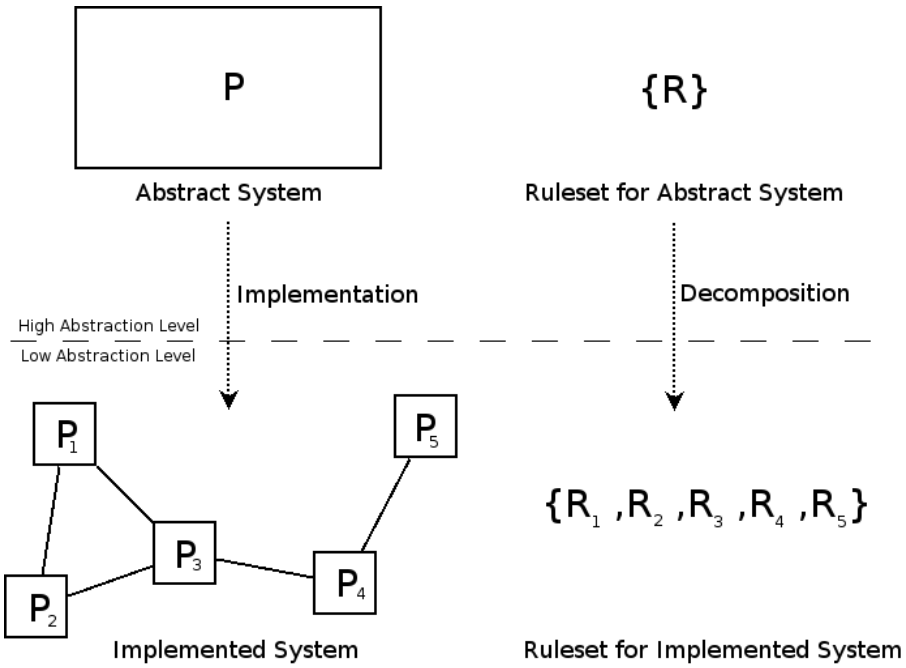


Figure 10: Abstraction Levels for Systems and Rules

To perform the decomposition process, some more attributes have to be defined for the implemented system: We need to know what capabilities parts in the system have or will have, and how to translate concepts in the rule from concepts for the abstract system to concepts for the implemented system. These attributes are called the *properties* of the system.

4.3.1 System Capabilities

System parts have functions they can perform that are defined as a list of capabilities. In an existing system, these capabilities will be very precisely defined so that a resulting decomposition can be directly assigned to the system parts, but in a system in developmen, they will be more general and abstract; the resulting decomposition will then tell the developer which system part should implement what functionality.

Definition: S is a mapping of capabilities to system parts that have those capabilities. Capabilities are defined as events, conditions, actions and functions.

$$capabilities = events \cup conditions \cup actions \cup functions$$
$$S \subseteq (system\ parts \times \mathbf{P}(capabilities))$$

It is possible that multiple system parts have the same capability. Capabilities can be four diffent things:

1) **Events** represent things that have happened in the system. An event may contain information about the occurance, or it may just be a token. When we say that a system part has the capability for an event, we mean that it has the capability to detect such an event.
2) **Conditions** are generally tests of system states, or system states in the context of event information. If a system part has a condition as a capability, it means that it can check that condition.
3) **Actions** are generally system procedures that execute a task.
4) **Functions** are operations or calculations that can be required as part of event or condition expressions, ranging from simple logical operations to complex tasks and math calculations.

Data that accompanies an event can be accessed through a variable. The variable originates from the event and can be used in functions, conditions and actions.

The most commonly used functions are the logical operators *and, or* and *not*. They can be used to combine events and/or conditions.

Besides logic-calculation functions, most system parts also have the capability to send and receive messages to and from other system parts that they are connected to. Which parts they have contact with is defined in the system definition. This capability is also assumed to be present on all system parts unless specifically stated otherwise.

4.3.2 Concept Translation

The abstract rules are often written without knowledge of the details of the implemented system. Such rules use terms to describe abstract concepts that the implemented system may not necessarily undertand. In order to decompose these rules we have to bring these concepts to a lower level of abstraction. To do this, we need a function that translates abstract concepts to concepts that the lower level system can handle.

Definition: T is a function that translates a set of rules to a new set of rule sets.

$$T(\textit{old rule set}) = \textit{set of new rule sets}$$

In this definition, the rule sets are subsets of the set of all possible rules.

In the example of the lightswitch in section 3.1 the action "*turn off the light*" could be an abstract concept. If the actual room contains three lamps, T will translate this concept from "turn off the light" to "turn off lamp 1, turn off lamp 2 and turn off lamp 3".

When T is implemented, the function is represented a set of tuples *(rule, rule)* where the first rule is any of the rules from the incoming rule set and the second is rule is the new rule that should replace it. T results in new possible rule set translations, in addition to the original. So when the set of tuples in T is empty, then $T(r) = \{r\}$. If T contains a single translation from r to r' then $T(r) = \{r, r'\}$.

$$T \subseteq (\textit{rules} \times \textit{rules})$$

In this definition, *rules* is the set of all possible rules.

For example: T could define a mapping like the following example of a doorbell in a store:

$$(\textit{customer entering store} \rightarrow \textit{sound bell} \;\Rightarrow\; \textit{doormat detects person} \rightarrow \textit{play bell sound})$$

We use ⇒ to distinguish between the old rule and the new rule. However, such a direct mapping as this will not be encountered very often. Often we need a partial mapping that only changes part of the rule, like this one for the intelligent light switch example:

$$\forall\, a \in \textit{events}, \forall\, b \in \textit{conditions}:$$
$$(a \bullet b \rightarrow \textit{Turn off the light} \;\Rightarrow\; a \bullet b \rightarrow \textit{Turn off lamp}\,1 \wedge \textit{Turn off lamp}\,2 \wedge \textit{Turn off lamp}\,3)$$

In this case, *events* is the set of all possible events and *conditions* is the set of all possible conditions. In a similar way we can write a partial mapping for *actions* and *functions*.

As a short-hand, we will write the above rule mapping like this:

$$(* \bullet * \rightarrow \textit{Turnoff the light} \;\Rightarrow\; * \bullet * \rightarrow \textit{Turnoff lamp}\,1 \wedge \textit{Turnoff lamp}\,2 \wedge \textit{Turnoff lamp}\,3)$$

When applying a translation to a rule, the result may be more than one rule. In that case, the mapping results in a set of rules like this:

$$\left(cust.entering \rightarrow sound\ bell \Rightarrow \left\{ \begin{array}{l} doormat\ detects\ person \rightarrow play\ bell\ sound \\ doormat\ detects\ person \wedge store\ is\ empty \rightarrow send\ notif.\ to\ manager \end{array} \right\} \right)$$

The transformation rule to translate one concept to another can become very complex,because all possible uses of the concept have to be addressed. As a shorthand for such a large translation, we describe in textform how one concept can be translated to another, like in the following example:

$$translate\ the\ concept\ \text{Patient}\ to\ the\ concept\ \text{Tag}\ with$$
$$an\ additional\ condition : hasRole(\text{Tag}, \text{PatientRole})$$

4.3.3 The Decomposition Algorithm

Now that we have the definitions needed to decompose a rule set for an abstract system to a rule set for a lower level system, we will define the algorithm. We have the definition of the lower level system *(L,G)*, the definition of the rule set ***R*** and the *properties* of the system *(S,T)*. The abstract rule set ***R*** is then decomposed to a valid rule set for the implemented system.

Definition: Given a rule set ***R*** with *n* rules and a low level system (*L,G)* with properties *(S,T)*, the decomposition process is defined as a function that decomposes ***R*** into $\boldsymbol{R_d}$.

$$\boldsymbol{R_d} = Decompose(\boldsymbol{R}, L, G, S, T)$$

$$Decompose(\boldsymbol{R}, L, G, S, T) = \left\{ \begin{array}{l} D(L, G, S, T(R_0)), D(L, G, S, T(R_1)), \ldots, \\ D(, L, G, S, T(R_{n-1})), D(, L, G, S, T(R_n)) \end{array} \right\}$$

In this definition, *T(r)* is the application of the translation mappings to *r*. The function *D* decomposes a single rule.

When implemented, *D(L,G,S,T(r))* works like this:

(1) For each resulting rule set from *T(r)*, find a match for the events, functions and actions in the rules in the capability list *S*. When an event, condition, function or action can be executed by more than one system part, this results in multiple matchings. Each of these matchings results in a new possible decomposition rule set.
(2) Construct a directed graph for each rule set from (1) (we explain below how a directed graph for a rule can be constructed).
(3) For each graph, determine the required communication and find a path in *(L,G)* between each pair of system parts in the required communications.
(4) For each communication path found in (3), apply sending action and receiving event substitution in the results of (1) corresponding to the graph from (2), so that there is a rule for each node in the path.

A pseudo-code representation of the algorithm can be found in section 6.2.3.

Step (1) can result in more than one possible decomposition. It is not required that each of these decompositions go through the entire algorithm. If a translation from *T(r)* can not be matched in (1), the decomposition is invalid. If a matching from (1) has no possible communication path in (3), it is also invalid. Any invalid decomposition is discarded. If there are no valid decompositions for a rule, it can not be decomposed for this system.

A rule has a basic order in which it must be executed; the events and the conditions must be true before the actions are performed. But beyond that, no execution order is defined. To support the decomposition process, we have defined a specific order in which a rule is executed, so that the communication choices can be made: when the events in a rule occur, first the event expression is evaluated. If this expression holds true, the condition expression is then evaluated. If this is also true, the actions are executed in the order that they have been defined.

The directed graph mentioned in step (2) illustrates the *flow of execution* of a rule (see example in Figure 11). It is used to determine what communication is required and how to break up a rule when it must be partially executed on different system parts.

The graph is formed by starting with a tree graph for the event expression. The events are the end nodes and the functions that combine them form the branches. Another tree graph is formed for the condition expression and one for the actions. The tree graphs are then connected; the top of the event graph connects to each end node of the condition graph and the top of the condition graph to the bottom of the action graph.

As an example, consider the following rule:

$$E_1 \wedge E_2 \bullet C_1 \vee C_2 \rightarrow A_1, A_2$$

The directed graph in Figure 11 shows the flow of execution for the rule. If we then assign system parts to perform parts of the rule, we can immediately determine what communication is required.

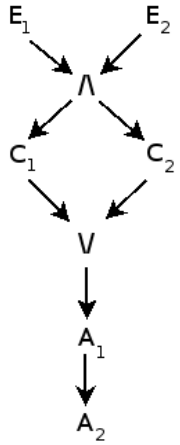


Figure 11: Directed graph.

If ***R*** is the rule set before translation and $\boldsymbol{R_d}$ the rule set after, then ***R*** and $\boldsymbol{R_d}$ must have *equivalent observable behaviour*. When looking at the system with the rules as a black box, the observed behaviour should be the same before and after the translation.

The decomposition algorithm changes the contents of the rules in two positions: during the translation phase and during the substitution of communication events and actions. This demand for equivalency is put on both the translation table and the communication substitution. Each translation step in the translation table must yield the same behaviour. Because the translation table is defined by system designers, they have to make sure this demand is met. If a translation step in the table results in non-equivalent behaviour, then the decompositions made using that table have incorrect behaviour.

The communication substitutions can only result in equivalent behaviour if the communication is reliable. If the communication is unreliable, the execution of a rule can halt halfway through because a message concerning an event is not passed to another system part. In this report, we consider communication to be reliable, for the sake of simplicity. What the consequences of unreliable communication may be, is discussed in chapter 7.

4.4 Examples

In this section we give three examples: An example showing a simple transformation of a rule, an example that shows alternative decompositions of a rule and an applied example from the elderly home scenario.

4.4.1 Simple Transformation

This example describes a simple system with two parts *x* and *y*, that can communicate directly. Part *x* can detect event *E* and part *y* can perform action *A*. For this system, we have a rule that describes that whenever *E* occurs, *A* should be performed. Through the application of some simple steps, the example explains how the rule can be decomposed so that there is a rule for *x* and a rule for *y* which only contain expressions that can be performed locally on *x* and *y* respectively.

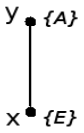


Figure 12: example system

For this simple example no translation is necessary, which means that *T* is empty. If we represent the example above in the formal definitions, it looks like this:

The system definition:

$$L = \{x, y\}$$
$$G = \{(x, y)\}$$

The system properties definition:

$$S = \{(x, \{E\}), (y, \{A\})\}$$
$$T = \emptyset$$

The rule set defininition:

$$\boldsymbol{R} = \{\boldsymbol{R_0}\}$$
$$\boldsymbol{R_0} : E \rightarrow A \quad (1)$$

Now we perform the decomposition algorithm on $\boldsymbol{R}$ so that it can be executed by the system.

At first we should apply the translation steps in *T* to $\boldsymbol{R}$, but because *T* is empty, we can skip this phase and continue. Next we try to match the conditions and actions used in $\boldsymbol{R}$ to *S*. This is possible, because *x* has capability *E* and *y* has capability *A*. We then rewrite (1) to include this information:

$$\boldsymbol{R_0'} : E_x \rightarrow A_y \quad (2)$$

Now that we know that x and y are involved in this rule, we look at *G* to see if *x* and *y* can communicate. That is possible because there is a direct path from *x* to *y*. Because the path contains two different system parts, the result of rewriting (2) becomes a rule set consisting of two rules: one for system part *x* and one for system part *y*:

$$\boldsymbol{R''} = \{\boldsymbol{R_x}, \boldsymbol{R_y}\} \quad (3)$$

If we consider (2) in the context of *x*, we conclude that the event can be handled locally, but the action can not. According to the path we found in *G* communication with y is possible, so for $\boldsymbol{R_x}$ we rewrite the action A_y as an action *S* that sends communication to part *y* with the event as a parameter:

$$\boldsymbol{R_x}: E \rightarrow S_y(E) \tag{4}$$

The action $S_y(E)$ sends a message to *y* concerning *E*.

Similarly, if we consider *y* we conclude that the action *A* can be performed locally, but the event can not. According to the path found in *G* we can expect incoming communication from *x*, so for $\boldsymbol{R_y}$ we replace E_x with an event *R* that receives communication from *x* with the parameter *E*:

$$\boldsymbol{R_y}: R_x(E) \rightarrow A \tag{5}$$

The event $R_x(E)$ occurs when a message is received from *x* concerning *E*.

Rules (4) and (5) can be performed locally on *x* and *y,* respectively. Rule sets ***R*** and ***R''*** describe the same observable behaviour, but where ***R*** describes the behaviour for the whole system, ***R''*** describes the behaviour for each system part. ***R''*** is the decomposition of ***R*** for this system.

4.4.2 Transformation with Alternative Decompositions

Consider a system with four parts connected as shown in Figure 13:

$$L = \{x, y, z, q\}$$
$$G = \{(x, z), (y, z), (z, q)\}$$

With the properties:

$$S = \{(x, \{E_1\}), (y, \{E_2\}), (z, \{'\wedge'\}), (q, \{A, '\wedge'\})\}$$
$$T = \emptyset$$

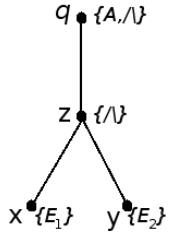


Figure 13: Second example system

We want to decompose the rule set ***R***:

$$\boldsymbol{R} = \{\boldsymbol{R_0}\}$$
$$\boldsymbol{R_0}: E_1 \wedge E_2 \rightarrow A$$

This example shows logic in the event clause in the form of the *and* ('Λ') function. From S we conclude that both system parts *z* and *q* can perform this function. *T* is empty, so the translation step does not change the rule set.

Starting the decomposition process, we can match ***R*** to *S*:

$$I: \boldsymbol{R_0'}: E_{1(x)} \wedge_z E_{2(y)} \rightarrow A_{(q)}$$
$$II: \boldsymbol{R_0'}: E_{1(x)} \wedge_q E_{2(y)} \rightarrow A_{(q)}$$

Because the *and* function can be executed by both z and q, two decompositions are possible. We first look at decomposition I:

$$\boldsymbol{R}_{\boldsymbol{0}}^{'}: E_{1(x)} \wedge_z E_{2(y)} \rightarrow A_{(q)}$$

Because this rule involves several system parts that must communicate, the explanation of how the decomposition works requires some more intermediate steps than the last example.

First we construct a directed graph that shows the flow of execution (Figure 14).

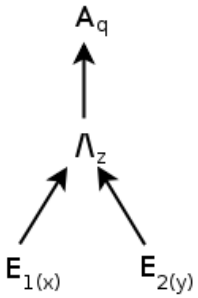


Figure 14: Directed Graph

We construct this graph to see if and what communication is required. It shows that in order to execute A_q in the rule, the *and* function must be evaluated first, which depends on the events E_1 and E_2. From this we can conclude that communication is required from x to z, from y to z, and from z to q.

We can then use the same substitution with sending actions and receiving events as in the first example to arrive at the following decomposition:

$$\begin{aligned}
&\textit{Decomposition I}: \\
&\boldsymbol{R}_{\boldsymbol{x}}: E_1 \rightarrow S_z(E_1) \\
&\boldsymbol{R}_{\boldsymbol{y}}: E_2 \rightarrow S_z(E_2) \\
&\boldsymbol{R}_{\boldsymbol{z}}: R_x(E_1) \wedge R_y(E_2) \rightarrow S_q(E_1 \wedge E_2) \\
&\boldsymbol{R}_{\boldsymbol{q}}: R_z(E_1 \wedge E_2) \rightarrow A
\end{aligned}$$

Similarly, we can construct a tree for the second decomposition (omitted) and determine that communication is required from x to q and from y to q. This leads to the following end result:

$$\begin{aligned}
&\textit{Decomposition II}: \\
&\boldsymbol{R}_{\boldsymbol{x}}: \quad E_1 \rightarrow S_z(E_1) \\
&\boldsymbol{R}_{\boldsymbol{y}}: \quad E_2 \rightarrow S_z(E_2) \\
&\boldsymbol{R}_{\boldsymbol{z}}: \quad R_x(E_1) \rightarrow S_q(E_1) \quad \textit{for path}(x,z,q) \\
&\qquad\quad R_y(E_2) \rightarrow S_q(E_2) \quad \textit{for path}(y,z,q) \\
&\boldsymbol{R}_{\boldsymbol{q}}: \quad R_z(E_1) \wedge R_z(E_2) \rightarrow A
\end{aligned}$$

We can observe from the amount of sending actions in both I and II that the first decomposition requires less use of the network, but we can also see that the second decomposition requires less calculation by the connecting system part z. Which of these decompositions would be used depends on what additional requirements have been defined for the decomposition of $\boldsymbol{R}$.

Multiple decompositions of a system can be possible because of similar capabilities found in *S* or because of multiple possible translation steps in *T*. In the above example, both *z* and *q* can execute the *and* function, so two decompositions are possible. If we would specify that all nodes can perform the *and* function, that would lead to four possible decompositions.

4.4.3 Elderly Home Example

This example involves a simplified system for the elderly-home scenario. We assume the availability of sensors that can detect people, a server application that can retrieve information from a database and contact people, a database that can forward messages and a gateway that has a connection to the sensor network and can write data into the database. For the example we look at a rule that describes the following behaviour:

When a patient is detected in a restricted zone, close the door in that zone.

If we represent this rule in our rule language, it looks like:

$$(Detected(Patient) \bullet LocatedIn(Patient, RestrictedZone) \rightarrow CloseDoor(RestrictedZone))$$

This top-level rule describes the system's behaviour.
The system is defined as follows (Figure 15):

L = { server application, restricted sensor nodes, allowed sensor nodes, gateway, database
}
S = { (server application, {HasRole, logic functions}),
(restricted sensor nodes, {DetectTagRestricted, CloseDoor}),
(allowed sensor nodes, {DetectTagAllowed})
}

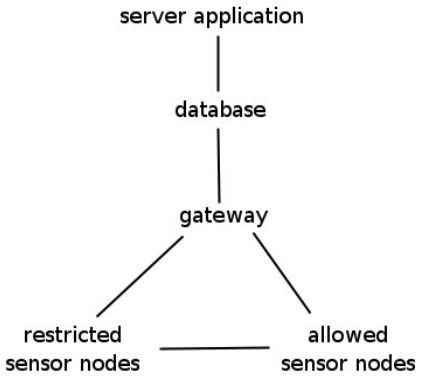


Figure 15: Graph G. The database forms a necessary router between the server application and the gateway, which is imposed as a restriction by the technology used (see Appendix A).

T = {
Translate "*Patient*" to "*tag*" with an extra condition "*hasRole(tag,PatientRole)*",

$$(Detected(tag) \bullet LocatedIn(tag, RestrictedZone) \rightarrow * \Rightarrow \; DetectTagRestricted(tag) \rightarrow *),$$

$$\left(\begin{array}{l} DetectTagRestricted(tag) \bullet * \rightarrow CloseDoor(RestrictedZone) \Rightarrow \\ DetectTagRestricted(tag) \bullet * \rightarrow CloseDoor \end{array} \right)$$

}

We can conclude from the definitions above that in this system, determining if a patient is in a certain zone type is equivalent to them being detected by a sensor in that zone. The sensor nodes that can detect people have no knowledge of the roles of people, which

means that the rule cannot be executed by a single device and decomposition is required.

Given the definitions above, we now apply the decomposition process on the rule. First we use the translation table *T*. When the translations steps are applied, the following rule is generated:

$$(DetectTagRestricted \quad (tag\ t) \bullet hasRole\ \ (t, PatientRole\ \ ) \rightarrow CloseDoor\ \ )$$

Next we construct a tree diagram from this rule, as shown in Figure 16:

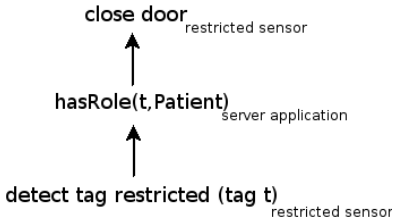


Figure 16: Tree diagram

Because *hasRole* is a function that uses a variable *t* that originates from event *DetectTagRestricted*, communication is required to allow the function to use *t*. In other words, the result of *DetectTagRestricted* has to be sent to the *hasRole* function. If the *hasRole* function then evaluates to true, the action *closeDoor* can be performed. As we can see from Figure 16, this involves communication from restricted sensors to the server application and from the server application to restricted sensors.

When the communication from the tree diagram is expressed in sending and receiving actions, the following rule set is generated:

Restricted sensors:

$$(DetectTagRestricted\ (tag\ t) \rightarrow send\ (DetectTagRestricted\ (t))\ to\ gateway)$$
$$(Receive(CloseDoor)\ from\ gateway \rightarrow CloseDoor)$$

Gateway:

$$\begin{pmatrix} Receive\ (DetectTagRestricted\ (tag\ t))\ from\ \ restricted\ sensor \rightarrow \\ send\ (DetectTagRestricted\ (t))\ to\ database \end{pmatrix}$$
$$(Receive(CloseDoor)\ from\ \ database \rightarrow send\ (Detected\ (tag))\ to\ restricted\ sensor)$$

Database:

$$\begin{pmatrix} Receive\ (DetectTagRestricted\ (tag\ t))\ from\ \ gateway \rightarrow \\ send\ (DetectTagRestricted\ (t))\ to\ server\ application \end{pmatrix}$$
$$(Receive(CloseDoor)\ from\ \ server\ application \rightarrow send\ (Detected\ (tag))\ to\ gateway)$$

Server application:

$$\begin{pmatrix} Receive\ (DetectTagRestricted\ (tag\ t))\ from\ \ database \bullet hasRole(t, Patient) \rightarrow \\ send\ (CloseDoor)\ to\ database \end{pmatrix}$$

The rules assigned to the restricted sensors are assigned to the whole group of sensors. In this example, the decomposition ends here. In an actual implementation, further decomposition on these rules may be required for the group of sensor nodes to arrive at rules that can run on each individual sensor.

The resulting decomposition is not very efficient, since every time a tag is detected by a sensor in a restricted zone, it must inform the server, because only the sensor can check if the detected person is a patient. If the sensors had the capability to perform (part of) the *hasRole* function, far less messages would have to be sent over the network.

5 Applying Rules to the Scenarios

Using the definitions from the previous chapters, it is possible to apply the rules approach to the problems defined in the scenarios. First we discuss how rules and rule decomposition affects the elderly home scenario, which is the basis for the prototypes. We consider requirements, the user interactions and the rules that we can derive from the scenario. Then we will define an architecture for the system. Following that we will discuss how rules affects the other two scenarios. At the end of this chapter we discuss the architecture of the middleware that supports rule decomposition.

The required system posed in the elderly-home scenario (section 2.1) can be developed with a rules-based approach. To do this, we need to define the architecture for the system and the abstract rules that define the system behaviour, and then decompose those rules. The resulting rule set can then be implemented to arrive at the working system. In this section we will discuss the requirements, user interactions, rules and architecture. The decomposition is discussed with the implementation in chapter 6.

5.1 Requirements

First, we consider the requirements that we can derive from the Elderly Home scenario. The abstract rules are directly based on these requirements. The following requirements can be identified in the scenario:

Tracking of location
The scenario defines the following system requirement:

> "To track people in and around the home, to use this tracking information to decide whether a patient has wandered off and to generate an alarm message to caregivers in the ward."

The main function of the system will be to determine if patients are in areas they are allowed to be in and to track their movement if necessary. If a patient enters an area that they are not allowed to enter without a caregiver or visitor as a guide, the system needs to check if there is a guide and inform the caregivers with a message if there is not. The administrators divide the building into three different types of zones, that are used by the system. These areas consist of admissable zones (green), non-admissable zones (red) and admissable zones close to non-admissable zones (yellow).

Daycare room

> "Part of the ward is a daycare room, which is a large recreation area where patients walk in and out all day. A caregiver must be present in the daycare room at all times as long as there are patients present. The administration wants an indicator to be visible somewhere in and around the daycare room that shows if it is unattended or when the last caregiver leaves the area while patients are still present."

This requirement is already literally defined in the scenario. The indicator is a set of lights placed inside and outside of the daycare room, that can be turned on and off using an electronic switch.

Privacy

> "However, since the patients are entitled to their privacy it is undesirable for the system to constantly track the location of everyone in the ward. To support this, location information should not be forwarded by the sensor network if a patient is in a green zone."

The system should ensure the privacy of the patients whenever possible. Interceptable communication that contains privacy sensitive information should be kept to a minimum. Location information of patients is considered privacy sensitive information.

Smart door

> "The main entrance door to the ward is a special location. This door has an electromagnetic locking mechanism, which needs to be turned on when a patient approaches the door from inside without guidance."

The system needs to provide the door with instructions to open or close the lock depending on the proximity of patients and caregivers.

The following requirements are not explicitly stated in the scenario, but can be derived implicitly:

Privacy exceptions
It should be possible to disable the privacy protection, in an emergency situation (e.g. a fire) when it is highly desirable that the location of all patients can be quickly determined. It is also possible that a patient is carrying some sort of healthsensor to monitor a medical condition that can detect an alarm situation, if such a situation happens then location data of this patient should be available immediately. Only certain people should be allowed to declare an emergency situation like this, and only certain people should have access to the location data.

Technology
To make this system work, a technology is required that is able to track people in the home with a minimum amount of invasiveness. Practice has shown that a technology with too much invasiveness such as a bracelet or an ankle strap is not accepted by the patients and they will then spend a lot of time trying to remove such technology.

One possible technology, which is the technology used in the prototypes, is that of sensor networks and is described in *Appendix A*.

Status messages
Depending on the technology used, indication messages need to be sent to administrators when a sensor or tag that is running on batteries expects to be unavailable soon, because e.g. its power is low.

5.2 User Interactions

This section discusses interactions that users can have with the system. We use those to identify some technology-related requirements for the system.

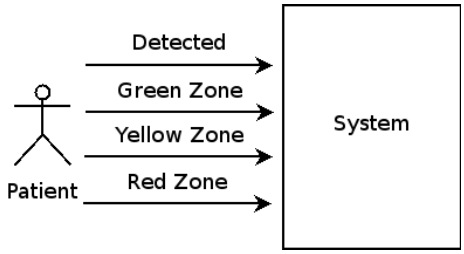


Figure 17: Patient interactions.

Patient interactions with the system (Figure 17):

- The system registers that a patient walks around carrying a tag.

The system should be able to connect one or more tag signatures with a patient. The relation may not always be one-to-one, a patient can have several tags and may not be carrying all of them with him. The tags that are not with the patient should not be included in the location approximation.

- The system registers that a patient enters a green area.
- The system registers that a patient enters a yellow area.
- The system registers that a patient enters a red area.

The system should be able to determine in what type of area a patient is moving, and depending on the situation, track the location or take certain actions.

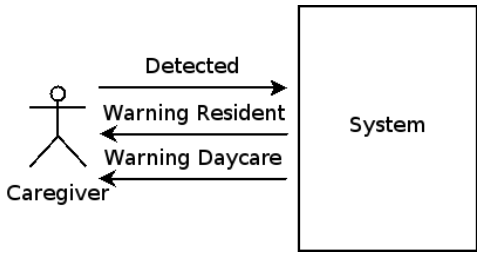


Figure 18: Caregiver interactions.

Caregiver interactions with the system (Figure 18):

- The system registers that a caregiver walks around carrying a tag and a mobile receiving device.
- A caregiver receives a warning message that a patient has entered a red area unsupervised.
- A caregiver receives a warning message that there is no caregiver in the daycare room.

The system should be able to track the location of a caregiver and send messages to them.

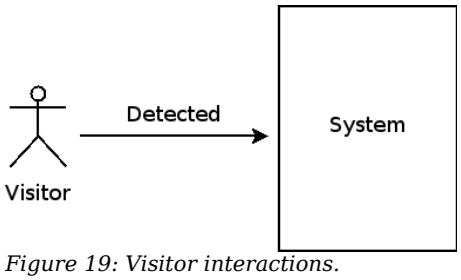


Figure 19: Visitor interactions.

Visitor interactions with the system (Figure 19):

- The system registers that a visitor walks around carrying a tag.

A patient guided by a registered visitor should not trip an alarm when entering a red zone. This requires the system to keep track of the location of visitors.

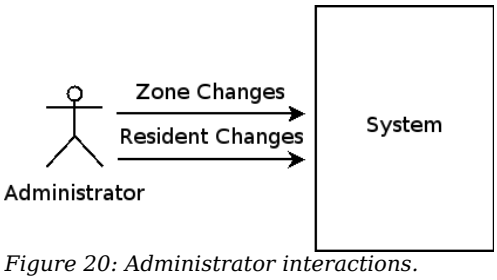


Figure 20: Administrator interactions.

Administrator interactions with the system (Figure 20):

- An administrator changes the list of patients.
- An administrator changes the placement or classification of an area (green, yellow or red).

New patients move into the ward as older patients pass away or move to other wards. The system should allow changing the list of patients and propagate this change to the whole system. The system should also allow changing the placement or the classification of areas and propagate this change to all the nodes in the network.

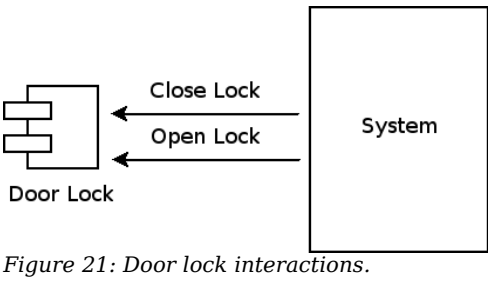


Figure 21: Door lock interactions.

Door lock interactions with the system (Figure 21):

- The system tells the door lock to close.
- The system tells the door lock to open.

The door lock on the ward entrance door can be triggered electronically, the system needs to tell it when to open or close.

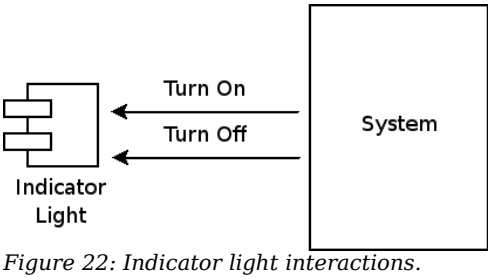


Figure 22: Indicator light interactions.

Indicator light interactions with the system (Figure 22):

- The system tells the indicator lights to turn on.
- The system tells the indicator lights to turn off.

The indicator light in and around the daycare area can be triggered electronically, the system needs to tell the lights to turn on or off.

5.3 Rules

The requirements can be used to derive a set of rules that define the system's required functionality.

The following rules have been defined regarding the location tracking requirement:

> *When a patient enters a red zone and that patient is not guided, sound an alarm to all caregivers.*
>
> *When a patient enters a yellow zone with a door and that patient is not guided, lock that door.*

Regarding the daycare indicator requirement:

> *When a patient is in the daycare room without a caregiver present, turn on the indicator.*
>
> *When a caregiver enters the daycare room and the indicator is on, turn off the indicator.*

Regarding the system administration:

> *When an administrator changes the zones or the patient list, update the proper definitions in the system.*

The privacy requirement does not translate into a set of rules, but rather into a requirement for the rule decomposition. When the sensor network sends detection

messages about a tag out to the gateway, this is personal information that can be intercepted. So if possible, the decomposition that has the minimal amount of message exchanges concerning location sent via the sensor network should be selected.

5.4 Architecture

Figure 23 shows the interaction of people and 3rd party components with the system and identifies four internal system parts:

1) A sensor network detects tags belonging to patients, visitors and caregivers. The nodes in the network can send data to the gateway.
2) The gateway can process data from the sensor network and enter it into the database, or act on data that is in the database.
3) The database can inform the server and the gateway when new data has arrived, and it can store data entries.
4) The server can read from the database, perform complex calculations and send messages to the caregivers. The server also has an interface for system administration.

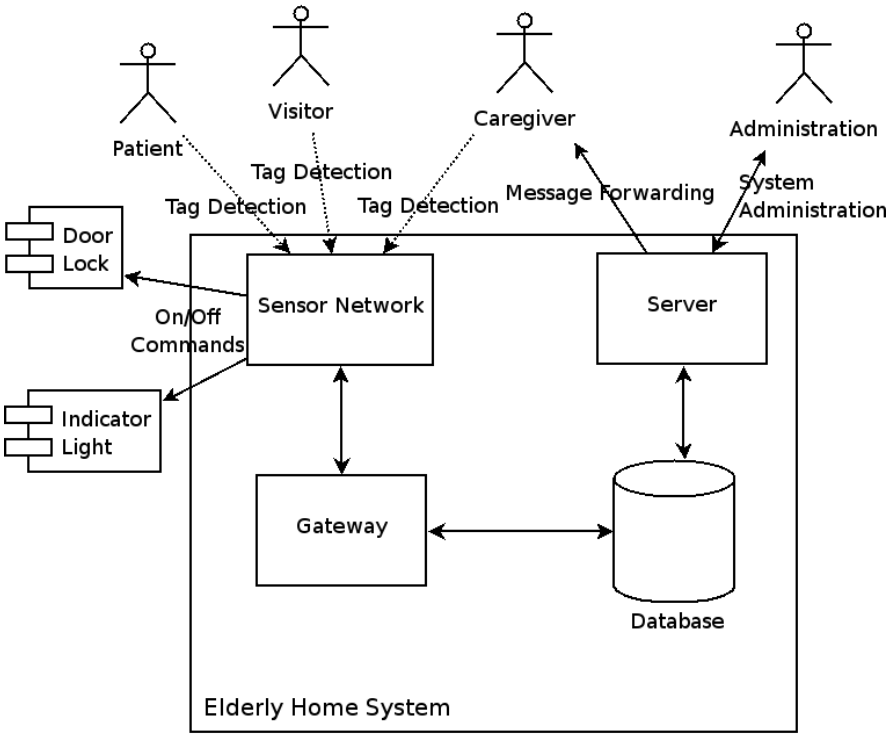


Figure 23: Elderly-home system architecture. The dotted lines show incoming events, the solid lines show outgoing events.

5.5 Capabilities

Table 1 describes the capablities of the system parts in the elderly-home system architecture. This table is used to define the properties for the prototypes in chapter 6.

Server	processing capabilities: – can translate patient info to tagIDs and back – can retrieve a tag's location – can match a location to a zone – can perform extensive generic calculations communication capabilities: – can contact caregivers by telephone – can store or retrieve data from the database
Sensor Network	processing capabilities: – can detect a tag – can interface with a device attached to the node (limited to on/off commands) – can perform limited calculations communication capabilities: – can communicate with other sensor nodes – can communicate with the gateway
Gateway	processing capabilities: – can calculate the position of a tag based on detection reports by nodes communication capabilities: – can communicate with sensor nodes – can store or retrieve data from the database
Database	processing capabilities: – standard issue relational database functionality communication capabilities: – can inform the gateway or the server when new data has been entered

Table 1: System capabilities

5.6 Network Communication

The system architecture also shows the communication links in the system. We can also define some constraints for those communication links:

Server – database connection
Standard database connection allows the execution of queries and retrieval of results, with the addition of messages from the database that inform the server that there is new data. High bandwidth, low cost.

Gateway – database connection
Identical to the Server – database connection. High bandwidth, low cost.

Gateway – sensor node connection
The gateway is connected to one sensor node via a serial link. Random sensors can send messages to the gateway by sending a message to the gateway sensor-node which relays it through the serial link. The gateway can send messages to random sensors by attaching a destination adress to a message and sending it to the gateway sensor-node. Low bandwidth, low cost.

Sensor node Ad Hoc network
Allows communication between all the sensor nodes in the network. Communication between nodes costs battery power, so it is costly. Low bandwidth, High cost.

Looking at these constraints, we can conclude that the high cost of communication in the ad hoc network means that communication between nodes should be kept to a minimum. This requirement influences which rule decomposition is chosen from the decomposition results in chapter 6.

5.7 Rules in the Task Outsourcing Scenario and Emergency scenario

The main difference between the rules approach in the Elderly Home scenario and the other two scenarios is network dynamics. In the Elderly Home scenario, the list of participating nodes is fairly static, only occasionally a new system part is introduced. In the Task Outsourcing scenario and the Emergency scenario the list of system parts is very dynamic.

In the task outsourcing scenario, as the user moves from place to place, devices join and leave the network. Devices joining the network may bring along their own list of capabilities and translation rules, which should be considered when redecomposing a rule.

In the emergency scenario, the network topology is also dynamic, but in contrast to the roaming scenario, the network only becomes more complex, while the capabilities stay largely the same (there may be more devices that can do the same task) and it may be necessary to re-evaluate what task is performed on what device when new devices join the network.

5.8 Middleware Architecture

Figure 24 shows the middleware architecture concerning rules distribution. The “Decomposition and distribution assignment” consists of the decomposition compiler tool and processes the results from the compiler. The “Transport and Deployment” layer handles the distribution of the decomposed rules to the system parts.

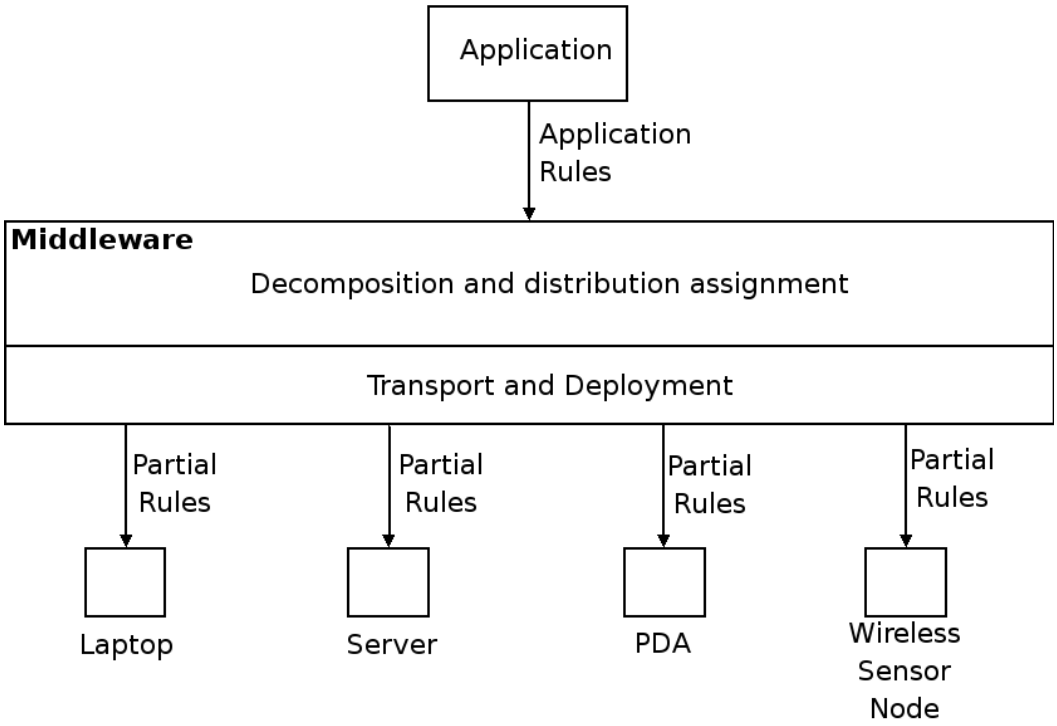


Figure 24: Overview of the first prototype's main middleware functionality.

This architecture is only relevant to the runtime use of decomposition. During development, the decomposed rules are used in the implementation of the software, and not distributed to the parts directly. With runtime use, the decomposition tool can either be run from a central point that generates the decomposed tools which are then distributed, or can be distributed in the network itself. In this case, decomposition is performed to generate rules when necessary (e.g. in real-time).

6 Implementation

Two prototypes have been built in this project. The first prototype is a proof of concept to show that rules decomposition can result in correct behaviour. It also provides the development environment for the second prototype. In the second prototype focus is on a decomposition compiler that can automatically decompose a rule when given a system definition and system properties.

This chapter first briefly discusses the first prototype in section 6.1, followed by the second prototype in section 6.2.

6.1 First Prototype

The first prototype is based on the Elderly Home Scenario (section 2.1), and is a proof of concept for our rules decomposition approach. This prototype also prepared a development environment for the second prototype.

6.1.1 Requirements

The main requirement of the first prototype is that it should demonstrate that a program using decomposed rules functions according to the behaviour defined by the orginal, non-decomposed rules.

Other requirements for the prototype implementation are the following:
- Simulate the sensor node network using the already existing simulator
- Translate the decomposed rules for the server application to code that can be understood by the rule engine.
- Translate the decomposed rules for the sensor nodes to PLT-scheme code [12] that the simulator can use.

The sensor network simulator was developed in the Smart Surroundings project [13]. It simulates a sensor network on a low level, using the same compiled binaries as the ones the actual nodes use.

6.1.2 Prototype Rule

The first prototype implements one rule:

When a patient is detected in a red zone, then sound an alarm.

This rule can be represented in our rule language as:

$$(DetectedInZone(Patient, Red) \rightarrow UpdateAlarm(Patient))$$

6.1.3 System Definition

The formal definition of the system *(L,G)* looks like this:

L = { sensor nodes, gateway, database, server application }

G = { (sensor nodes, gateway),
(gateway, database),
(database, server application)
}

6.1.4 Properties

The capabilities are based on Table 1 in section 5.5. In the first prototype, the sensor nodes have very limited capability. They can only detect the presence of a tag and relay this information to the gateway.
The gateway has the capability to perform calculations and store information in the database.
The server application can perform calculations, has access to the database, can relay information to the users of the system and incorporates a rule engine incorporated that can perform logical reasoning based on supplied data on demand.

S = { (sensor nodes, {detect tag}),
(gateway, {calculate location}),
(server application, {match location to zone, update alarm})
}

The system is schematically displayed in Figure 25.

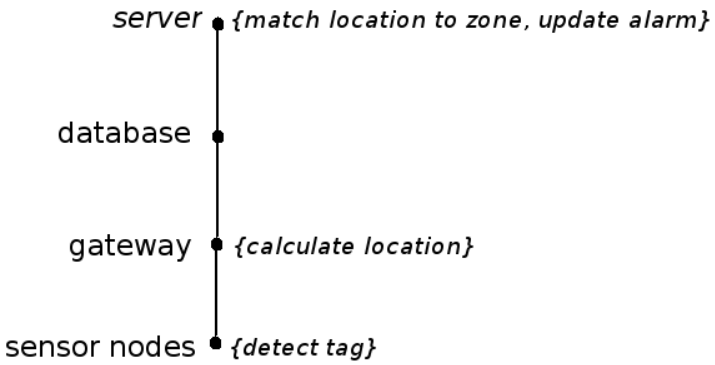


Figure 25: The system for the first prototype.

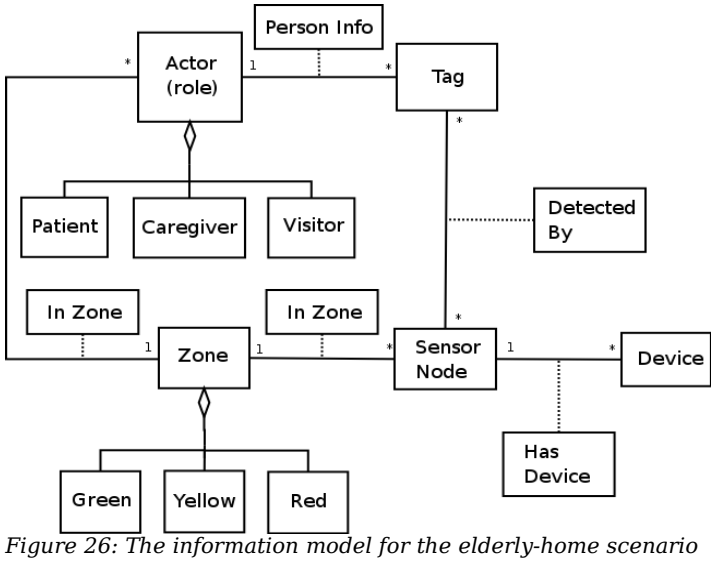


Figure 26: The information model for the elderly-home scenario

Figure 26 shows the information model for the prototype. A person is either a Patient, a Caregiver or a Visitor. Each person has a number of tags, and the person has one location in a zone. Each zone can have any number of sensor nodes, and each node can detect any amount of tags. A node can also have devices attached to it, which it can manipulate (such as the electric lock or the indicator light).

T includes translations that convert the abstract concept of a patient to a person with a tag and an assigned role as a patient. It also translates the abstract concept of a person being in a zone to a person having a location that falls within the boundaries of a defined zone.

6.1.5 Rule Decomposition

The rule from section 6.1.2 was manually decomposed, and results in four rules:

Sensor nodes:

$$(Detected(tag) \rightarrow send(Detected(tag)) to\ gateway)$$

Gateway:

$$\begin{pmatrix} Receive(Detected(tag))\ from\ sensor\ nodes \rightarrow \\ send(Location(tag, CalculateLocation(tag)))\ to\ database \end{pmatrix}$$

Database:

$$(Receive(Location(tag, location))\ from\ gateway \rightarrow Send(Location(tag, location))\ to\ server)$$

Server:

$$\begin{pmatrix} Receive(Location(tag, location))\ from\ database \bullet InZone(location, \text{red}) \rightarrow \\ UpdateAlarm(GetPersonInfo(tag), location) \end{pmatrix}$$

An alternative decomposition would be for the gateway to do no processing and to just store all data from the sensor network into the database and then let the server application do the location approximation. To arrive at this decomposition, the capability to calculate positional data should be added to the server. However, this decomposition is undesirable for the prototype: Besides the fact that this decomposition would result in a traditional architecture using a centralized server where all the work is done, the solution is also very inefficient in this situation. It forwards all detection data from the sensors straight to the server, while in the above solution, the gateway only needs to forward location data when the location has actually changed.

6.1.6 Result

A working environment was developed for this prototype. It includes the simulator, a java application that can control the simulator, an SQL database and java environments for the gateway, server and user interface.

The implementation of the decomposition from section 6.1.5 shows the behaviour as defined in the original rule, which shows that the decomposition process can work.

The gateway approximates tag location by determining which nodes heard the tag in the last 5 seconds, and averaging the locations of these nodes. Interestingly, the accuracy and response-time of the location is comparable to a current commercial solution, though admittedly that commercial solution is still under development.

6.2 Second Prototype

The second prototype centers around the implementation of a tool to automate rule decomposition. To demonstrate that the tool works, a set of rules is decomposed using the tool and the resulting rules are implemented in the working environment of the first prototype.

6.2.1 Requirements

The second prototype makes use of the development environment created for the first prototype to demonstrate that rules decomposed using the process described in this report display the required behaviour when implemented.

An additional piece of software is introduced: the compiler. The compiler decomposes rules for a given system and displays the possible decompositions for the user. We then manually pick a decomposition, implement the decomposed rules and check to see if the system's behaviour is what we expected.

Requirements for the second prototype:
- Decomposition compiler that decomposes abstract rules into lower level rules.
- Implement the decomposition generated by the compiler that puts more functionality at sensor nodes compared to the first prototype

6.2.2 Compiler Design

The compiler applies the decomposition algorithm to a given rule and system. As input, the compiler requires 3 parameters:

1) The rule to decompose *R.*
2) The system definition *(L,G).*
3) The system properties *(S,T).*

These paramters are supplied in the form of XML documents. The XML-schema definition for these files can be found in Appendix B. To decompose a set of rules, the tool has to be called for each rule separately.

The compiler returns a numbered set of possible decompositions of the rule, ordered by system part. If a rule cannot be decomposed because a capability cannot be matched or a communication path cannot be found, it returns with an error for that decomposition.

A simple example that demonstrates how the tool can be used is shown in Figure 27. We assume the following parameters:

$R_0 = E \bullet C \rightarrow A$

$L = \{x, y\}$

$G = \{(x, y)\}$

$S = \{(x, \{E, C\}), (y, \{A\})\}$

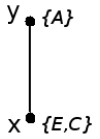


Figure 27: Example system

The XML representation of this example can be found in Appendix B.

Using the tool on the above rule results in the following decomposition:

$R_x : E \bullet C \rightarrow Send(C)\ to\ y$

$R_y : Receive(C)\ from\ x \rightarrow A$

Appendix B also contains a second, more elaborate example.

6.2.3 Algorithm

The compiler implements the algorithm defined in Chapter 5. In pseudo code, the algorithm looks as follows:

```
read rule data, system data, property data
initialize finished decomposition set as empty, initialize ...
            ... possible decomposition set as empty
add rule to possible decomposition set
loop
      find matchings of translation steps to entries in ...
            ... possible decomposition set
      if any exist and step has not been marked as applied
            apply translation
            add result to possible decomposition list
            mark step as applied for the found matching
            continue with next loop run
      end if
      if no matching unapplied translation steps exist
            break loop
      end if
end loop
for each element of possible decomposition set as n
      get list of rule mappings of n to capability list as k
      if any parts of rule cannot be mapped to capability list
            discard n
            continue with next possible decomposition
      end if
      for each element of k as m
            try to find communication paths for m
            if all paths exists
                  generate communication rules for m
                  add generated rules to finished decompositions
            end if
            if not all paths exist
                  discard m
            end if
      end for
end for
```

At the end of the algorithm, the finished decomposition set will contain all possible decompositions of this rule.

6.2.4 Decomposition

The rule used in the second prototype which was decomposed using the compiler tool, is the following:

$$(Detected(patient, zone) \bullet isYellow(zone) \rightarrow CloseDoor(zone))$$

The rule is rather simple, but even then the resulting decomposition is quite long as we show in this section.

The system is identical to the one used in the first prototype, namely:
L = { sensor nodes, gateway, database, server }

G = { (sensor nodes, gateway),
(gateway, database),
(database, server)
}

We use two different system properties to arrive at a different decomposition using the same rule and the same system definition. The translation table remains the same, we only change the capability list to get to the different decompositions.

T = {

$$(Detected(patient, zone) \bullet * \rightarrow * \Rightarrow Detected(tag, zone) \bullet * \wedge isPatient(tag) \rightarrow *),$$

$$\left(\begin{array}{l} Detected(tag, zone) \bullet isYellow(zone) \wedge * \rightarrow * \Rightarrow \\ Detected(tag) \bullet inYellowZone(LocationOf(tag)) \wedge * \rightarrow * \end{array} \right),$$

$$(* \bullet * \rightarrow CloseDoor(zone) \Rightarrow * \bullet * \wedge isInZone(ZoneOf(LocationOf(tag))) \rightarrow CloseDoor)$$

}

After applying T, the rule looks like:

$$\left(\begin{array}{l} Detected(tag) \bullet (inYellowZone(LocationOf(tag)) \wedge isPatient(tag)) \wedge \\ isInZone(ZoneOf(LocationOf(tag))) \rightarrow CloseDoor \end{array} \right)$$

First Decomposition

For the first decomposition, we use the following capability list:

S = { (sensor nodes, {Detected, isInZone, CloseDoor}),
(gateway, {LocationOf}),
(server, {isPatient, inYellowZone, ZoneOf})
}

Using these paremeters, the tool results in the decomposed rule set discussed below.

When the sensor nodes detects the *Detected* event, it will send both a notice about this and the encountered tag data on to the gateway. When a sensor node receives a token message from the gateway that a tag was found that is a patient and was in a yellow zone, the node will check if it is in the zone of that tag and if that is true, it will perform the *CloseDoor* action.

Sensor Nodes:

$$(Detected(tag) \rightarrow Send(Detected(tag)) to\ gateway)$$

$$(Detected(tag) \rightarrow Send(tag) to\ gateway)$$

$$\left(\begin{array}{l} Receive(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag)))) from\ gateway \wedge \\ Receive(ZoneOf(LocationOf(tag))) from\ gateway \bullet \\ (isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag)))) \wedge \\ isInZone(ZoneOf(LocationOf(tag))) \rightarrow CloseDoor \end{array} \right)$$

The gateway has four rules. When it receives notice of the *Detected* event happening, it will forward that to the database. When it receives tag data, the location of this tag is calculated and forwarded to the database. If it receives *ZoneOf* data about a tag from the database it forwards it to the sensor nodes. And finally, if it receives a token message that a tag is a patient and is in a yellow zone, it will also forward that to the sensor nodes.

Gateway:

$$(Receive(Detected(tag)) from\ sensor\ nodes \rightarrow Send(Detected(tag)) to\ database)$$

$$(Receive(tag) from\ sensor\ nodes \rightarrow Send(LocationOf(tag)) to\ database)$$

$$\left(\begin{array}{l} Receive(ZoneOf(LocationOf(tag))) from\ database \rightarrow \\ Send(ZoneOf(LocationOf(tag))) to\ sensor\ nodes \end{array} \right)$$

$$\left(\begin{array}{l} Receive(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag)))) from\ database \rightarrow \\ Send(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag)))) to\ sensor\ nodes \end{array} \right)$$

The database has four forwarding rules, it will send the *Detected* event and location data to the server and it will send *ZoneOf* and token messages that a tag is a patient and is in a yellow zone to the server.

Database:

$$(Receive(Detected(tag))\ from\ gateway \rightarrow Send(Detected(tag))\ to\ server)$$

$$(Receive(LocationOf(tag))\ from\ gateway \rightarrow Send(LocationOf(tag))\ to\ server)$$

$$\left(\begin{array}{l} Receive(ZoneOf(LocationOf(tag)))\ from\ server \rightarrow \\ Send(ZoneOf(LocationOf(tag)))\ to\ gateway \end{array}\right)$$

$$\left(\begin{array}{l} Receive(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ from\ server \rightarrow \\ Send(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ to\ gateway \end{array}\right)$$

The server has two rules. Firstly, when it receives a message that a *Detected* event has happened for a tag together with location data for that tag, it will check if that tag is a patient and if it is currently in a yellow zone. If this is true, a token message that respresents this is sent to the database. Secondly, if it receives location data for a tag, it will calculate the zone that tag is in, and send that to the database.

Server:

$$\left(\begin{array}{l} Receive(Detected(tag))\ from\ database \wedge Receive(LocationOf(tag))\ from\ database \bullet \\ isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))) \rightarrow \\ Send(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ to\ database \end{array}\right)$$

$$\left(\begin{array}{l} Receive(LocationOf(tag))\ from\ database \rightarrow \\ Send(ZoneOf(LocationOf(tag)))\ to\ database \end{array}\right)$$

Second Decomposition

In the second capability list the isPatient capability is assigned to the sensor nodes:

S = { (sensor nodes, {Detected, isPatient, IsInZone, CloseDoor}),
(gateway, {LocationOf}),
(database, {}*),
(server, {inYellowZone, ZoneOf})
}

Using these parameters, the tool results in a decomposition that is almost identical to the one above, except that the *isPatient* functionality is shifted to the sensor nodes using forwarding rules. This occurs because the tool does not reason about what happens in the messages. We present below that decomposition, but *manually optimized* using one observation: If we know that a tag is not a patient (if *isPatient(tag)* is false), then we can stop evaluating the rule. The difference between this decomposition and the first is discussed in the next section.

A sensor node will detect the event Detected when it happens. When it does, it checks if this tag belongs to a patient and if that is true, it sends both a token to indicate this and the tag data to the gateway. If it receives a token message from the gateway that indicates that the patient is also in a yellow zone, it will check if the sensor node is in the zone of that location and if that is true, it will perform the *CloseDoor* action.

Sensor Nodes:

$$(Detected(tag) \bullet isPatient(tag) \rightarrow Send(isPatient(tag))\ to\ gateway)$$

$$(Detected(tag) \bullet isPatient(tag) \rightarrow Send(tag)\ to\ gateway)$$

$$\left(\begin{array}{l} Receive(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ from\ gateway \wedge \\ Receive(ZoneOf(LocationOf(tag)))\ from\ gateway \bullet \\ (isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag)))) \wedge \\ isInZone(ZoneOf(LocationOf(tag))) \rightarrow CloseDoor \end{array}\right)$$

The gateway has four rules. If it receives a token message that indicates that the a patient has been detected, it will forward it to the database. If it receives tag data, it calculates the location of that tag and forwards the result to the database. If it receives *ZoneOf* data from the database it is forwarded to the sensor nodes and if it receives a token message that a tag is in a yellow zone it will do the same.

Gateway:

$$\left(Receive(isPatient(tag))\ from\ sensor\ nodes \rightarrow Send(isPatient(tag))\ to\ database\right)$$

$$\left(Receive(tag)\ from\ sensor\ nodes \rightarrow Send(LocationOf(tag))\ to\ database\right)$$

$$\left(\begin{array}{l} Receive(ZoneOf(LocationOf(tag)))\ from\ database \rightarrow \\ Send(ZoneOf(LocationOf(tag)))\ to\ sensor\ nodes \end{array}\right)$$

$$\left(\begin{array}{l} Receive(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ from\ database \rightarrow \\ Send(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ to\ sensor\ nodes \end{array}\right)$$

The database has four forwarding rules similar to the first decomposition.

Database:

$$\left(Receive(isPatient(tag))\ from\ gateway \rightarrow Send(isPatient(tag))\ to\ server\right)$$

$$\left(Receive(LocationOf(tag))\ from\ gateway \rightarrow Send(LocationOf(tag))\ to\ server\right)$$

$$\left(\begin{array}{l} Receive(ZoneOf(LocationOf(tag)))\ from\ server \rightarrow \\ Send(ZoneOf(LocationOf(tag)))\ to\ gateway \end{array}\right)$$

$$\left(\begin{array}{l} Receive(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ from\ server \rightarrow \\ Send(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ to\ gateway \end{array}\right)$$

When the server receives a token message that a patient has been detected and location data about the tag of that patient, it will calculate if that location is in a yellow zone and send the results back to the database. If the server receives location data from the database it will send the zone of that location back.

Server:

$$\left(\begin{array}{l} Receive(isPatient(tag))\ from\ database \wedge Receive(LocationOf(tag))\ from\ database \bullet \\ isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))) \rightarrow \\ Send(isPatient(tag) \wedge inYellowZone(ZoneOf(LocationOf(tag))))\ to\ database \end{array}\right)$$

$$\left(\begin{array}{l} Receive(LocationOf(tag))\ from\ database \rightarrow \\ Send(ZoneOf(LocationOf(tag)))\ to\ database \end{array}\right)$$

6.2.5 Observations

In this report we chose to present the two decompositions separately so that the decomposition differences caused by the different capabilities can be easily identified, but in practice both of these possible decompositions can be achieved in a single use of the tool by adding the 'isPatient' functionality at both the sensor nodes and the server.

We obtained two decompositions because there are two places where the 'isPatient' function can be performed. In practice, the logic functions ('Λ') also have to be assigned to the sensor nodes and the server. This results in a total of 8 different possible decompositions, which vary depending on where the two 'Λ' functions are performed. Two of those correspond to the ones presented above, we chose not to discuss the remaining decompositions in this report.

The two decompositions look very similar, but their performance is very different. When these two rule decompositions are implemented in the work environment from the first prototype, we observe that in the second decomposition the network traffic is reduced considerably, because sensor nodes will not start executing the rule for people who are not patients.

The network traffic could be reduced even further if a sensor also knows if it is in a yellow zone, which means sensor in other zones will not report detection. To arrive to this decomposition, another translation rule could be added that translates the zone check to a check if the sensor is in a yellow zone.

There is also room for improvement in the decomposition compiler, sometimes there are two rules on one system part to receive a message and forward it, and these rules could be combined into one rule that does those things at the same time.

7 Final Remarks

This chapter discusses the results of this project. First we discuss the results of the research questions in section 7.1. Next we discuss various issues and problems of the project in section 7.2. Finally we discuss possible future work on rules decomposition in section 7.3.

7.1 Research Results and Conclusions

Literature study shows that there are numerous solutions for context-aware application framework. Some solutions are designed for decentralized Ad Hoc networks, but there are none that allow the use of high abstraction rules to be performed in a distributed manner. Once the gap from high abstraction to low abstraction is bridged, some existing solutions can be used to perform the lower level rules in a distributed environment.

The two objectives of this project were:

1) To formally define a method to translate a rule written for a high level abstract system into rules for a distributed network.
2) To design and implement a framework that supports distributed context processing by allowing decomposition and distribution of application rules.

We defined the method for 1) in Chapter 4. The design for 2) was given in Chapter 5. The framework was partially implemented, the decomposition tool works (see Chapter 6), but the distribution of decomposed rules still has to be done manually.

The definition of the decomposition process and the implementation of the tool can be the basis for the development of a method to fully automate the distribution of an abstract rule over a distributed environment.

Rule decomposition used when developing a system with a distributed architecture can significantly speed up the development, because the designers and programmers do not have to take into account the distributed nature of the system. The designers can define rules that state what they want the abstract system to do, the programmers define how abstract concepts translate to practice and then the decomposition tool provides possible assignments of which devices should implement what functionality.

7.1.1 Reflection on Approach

Research study:
In the last 10 years, a very large amount of documentation has been written about context-aware applications. A good portion of the documentation deals with rules but only a few about rules in a distributed environment. Finding the relevant material took more time than was anticipated. Better preparation and search starting points could have saved some time.

Formal definition:
Defining a formal definition for something that has not been defined before, such as the decomposition process, takes a lot of time. Flaws in the initial definitions were quickly found when problems occured in the prototype implementation, which demanded revisiting the definitions. This was to be expected, since it was an iterative process.

Prototype:
The simulator of the sensor network iwas not a finished product, so it required a lot of work to prepare it for the prototype. Preparing the simulator took a lot of time because the simulator was written using a Python/Scheme combination, which was unknown to us at the time. Unfortunately this could not be avoided, because there was no alternative for this simulator.

The graphical user interface that showed the working of the prototype was simple to implement, because there was a ready-made solution available from WMC (writing one from scratch would have taken a lot of time).

7.2 Discussion

During the work done on this project, several issues came forward.

7.2.1 Realtime Decomposition

Is rule decomposition used at real-time practical? For scenarios like the Task Outsourcing scenario and the Emergency scenario, the rules are so simple that the only thing that is actually done is a redistribution of tasks, which does not necessarily require the use of rules. Rule decomposition only becomes really useful when more complex rules are decomposed.

If rule decomposition is used in realtime, the process must be performed fast enough. We expect that abstract rules will generally only have a limited size and use a limited range of expressions, but if the rule is very complex and the network is very large, the decomposition process can take up a large amount of processing to complete. Furthermore, information about the network topology and the capabilities has to be collected, which in the case of a dynamic wireless network can take some time. This means that there may be a limit to the complexity and size of rules and networks for real-time decomposition.

7.2.2 Alternative Use of Decomposition

In the definition of the decomposition process, we stated that there is a direct communication between two nodes if they can talk directly to each other through lower level communication protocols. This keeps the lower level routing information out of the decomposition process and makes it less complex. However, in certain situations it might be desirably to consider the lower level routing in the decomposition.

For instance, in an ad-hoc mesh network, including the routing means that it is directly visible how much the sending of a message will cost depending in the system parts involved. This can influence which decomposition is used, for instance to prefer decompositions with the minimal amount of communication routing. However, including this information may make the resulting rules practically unreadable by humans, which is not suitable for development.

7.2.3 Problems and Limitations

There are some practical problems and limitations that can be identified in the decomposition process.

As was mentioned in section 4.3, in this report we assume that communication is reliable. When communication is unreliable, it may happen that a message about an event is not delivered, and a rule decomposition is not executed. In this situation, the decomposition is not observably equivalent to the original rule. If the system allows it, redundancy may be introduced to improve reliability and depending on the system requirements the system may be able to cope with rules that have only fired half-way through, for instance by allowing roll-backs of actions that have already been taken.

The amount of possible decompositions from a single rule can be extremely large, depending on the system and the properties. In the case of a large distributed architecture with a lot of system parts that can perform exactly the same capabilities and the rule should only be executed once, the number of decompositions grows as a factor of the amount of system parts and capabilities. If all system parts should have the same behaviour, a solution is not to work with all instances of that type of system part,

but with the type instead.

The prototypes mix types of system parts (sensor nodes) with instances of system parts (gateway, database and server). Mixing types and instances of types together in an architecture can complicate the implementation of rules. A system part that has a rule that tells it to listen to a message from a type of system part, would need a separate rule for each instance of that type when implemented (see Figure 28). If that is a large group of instances, like for example in a sensor network, this could mean hundreds or thousands of rules. A possible solution to this problem is to have the message source disregarded in the case of a device type sending a message to someplace else. By doing this, the implementation would only require one rule which triggered by a message being received from an unknown source. This imposes natural limitations on the functionality of rules, because this would make it impossible to return a message back to the sender or to consider who sent it.

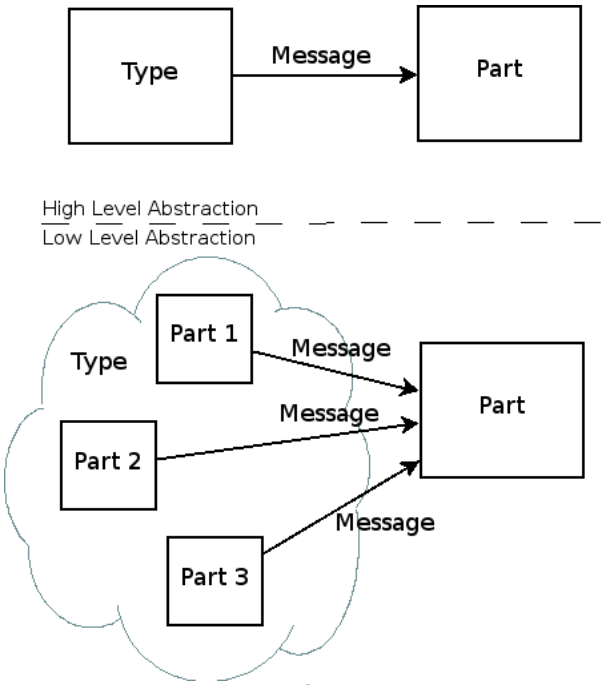


Figure 28: Mixing types and instances.

A general problem for rule execution is timing. When a rule says that it should be triggered when event E_1 and E_2 happen, what does that mean if these events are not synchronized? How large should the window of acceptance for E_2 be after E_1 is received? Should old event data be thrown away? This problem only arises for events and not for conditions, because in our approach the conditions are only evaluated when the event clause becomes true, which makes the condition statement inherently synchronized.

The timing problem also leads to another complication: when a rule uses several different events and those events are forwarded to several different devices, what happens when two identical events happen right after each other? Latency in the network may cause results from the second event to overtake the first, possible hampering the rule execution. How can this be avoided?

7.3 Future Work

There are several ways in which work can continue following this project.

7.3.1 Project Continuation

The formal definition of the decomposition process given in this report is probably not entirely correct, from a mathematical viewpoint. Especially the translation function

notation used is not type correct, and the definition will probably have to be changed to allow an actual proof of equivalency.

Prototypes have been built for the Elderly-Home scenario (section 2.1). The remaining two scenarios, the Task Outsourcing scenario (section 2.2) and the Emergency scenario (section 2.3), can be worked out in detail and be prototyped to investigate the decomposition process in real-time use.

The timing and repetition issues mentioned above should be solved. Possible solutions could include timestamps and sequence numbers. Currently, timing issues are simply ignored.

The methods and problems of mixing types and instances should also be better defined. The prototypes use a sensor node type, but work around the typing problem by treating all sensor nodes as a single system and assuming that there will be a further decomposition iteration for the sensor nodes (this was done manually in our prototype, which was not a complex task because the rules were simple).

7.3.2 Decomposition Tool

Translations:
The decomposition tool does not currently implement the algorithm defined in section 6.2.3 completely, because it does not allow the full expressiveness of the translations. Translations can be represented in the implementation by using Xpath [17]. An X-Path query can be defined that matches the parts of the rule that should be replaced, and pointers to those XML elements can be used to replace them and add new expressions.

Common translations that are often used can be gathered together in a standard library. Are there enough 'common' translations? This depends on what kind of functionality is used in the rules that are decomposed. Research needs to be performed to assert if the idea of a standard library of common translations is useful.

Optimization:
A lot of optimization could be added to the current decomposition process. For complex rules, the tool generates a lot of rules for system parts that are slightly different in context but have the same content. These rules could be combined in a single rule.

The process should also do some reasoning about the content of the rule. As we mentioned in section 6.2.4, the second decomposition presented was not what the tool actually returned, but it was optimized manually. If the tool reasoned about the fact that if the *isPatient(tag)* condition fails, the rest of the rule would not have to be evaluated, then the tool would return the optimized decomposition.

The tool could also swap the order of logic in the rule that results from translation before distributing, because the order of logic does not have a functional impact, but can have a tremendous impact on the amount of messages sent. For instance, in the second decomposition of the second prototype (in section 6.2.4), if the order of the “and” functions was swapped, the system would be forced to send twice as many messages, because it would first check if the location is in a yellow zone on the server, send that result to the sensor nodes, check if it is a patient there, then send that back to the server, etc. If the tool has the power to swap logic around to arrive at the most optimal order of execution, this means that the user does not have to think about ordering the logic expressions.

The tool could also preselect the presented decompositions. The tool now presents all decompositions of a rule, even though some of them may be clearly undesirable. Using message statistics and evaluation of how far rules are partially executed before it is concluded that the logic expressions will not evaluate to true, can lead to automatic detection of the most efficient decomposition.

Further Automation:
In the case of development use, the functionality can also be extended so that the tool translates the resulting decomposed rules directly into code or pseudo-code local to the system part, automating the programmers' work.

There are architectures for distributed rule engines, such as mentioned in Chapter 1. The decomposition tool can be made to export rules in a format that can be directly entered into those rule engines. Theoretically, this could lead to the full automation of rule distribution.

7.3.3 Parallel Use of Capabilities

A possible branch from the decomposition process is one that uses capabilities in parallel.

When several system parts have the same capability, currently the decomposition result of a rule that uses that capability consists of multiple possible decompositions, one for each system part that has the capability. In each of those decompositions only one of the capabilities is used. In some situations, it might be possible to have all these system parts performing this capability in parallel, potentially increasing efficiency. However, the capability must be suitable for parallel execution and parallel execution on separate system parts generates timing and synchronization problems that must be solved.

Appendix A: Elderly Home Technology

In section 2.1, we stated that a technology is needed that can track people in the home. The technology chosen for the prototype was a sensor network consisting of light duty sensor nodes (tags), heavy duty sensor nodes (sensors) and gateway systems to link the sensor network to a wired network (gateways). The sensor network used in the prototype consists of µ-nodes from Ambient Systems [1].

The complete system involves a number of different devices:

- The tags are small sensor nodes that have limited functionality and are small enough to be carried by people without being noticed. The tags are capable of reading a sensor and perform multi-hop routing, but to conserve power they are usually limited to acting as a locator beacon.
- The sensors are larger sensor nodes with a more powerful power supply and more functionality than the tags and are usually fixed to one position. The sensors form a multi-hop mesh network that covers the whole building. There is one sensor with extra functionality, which is connected to the main entrance door to the wing which has a magnetic lock that the sensor controls (See chapter 2.1.1)
- The gateways are devices that link the sensor network with the server application on a wired network.
- The data from the sensor network is written to a relational database, and only through this database can applications communicate with the sensor network. A database with extended functionality is available that can inform interested parties when new data is written into a table.

In different pieces of clothing of each patient tags will be embedded, so that a patient will always carry at least one tag at any given time, although this can never be 100% guaranteed. Each caregiver carries a tag and a mobile device that is capable of receiving messages from the server application and alerting the user. Certain visitors who help with the care of a patient are given a tag as well.

The sensors indicate which tag signals they detect within their range. The gateway combines the data from the sensors to extrapolate the location a tag is in at some moment in time.

There is a separate dedicated sensor on the entrance door, which has an interface to open or close the magnetic lock on the door. When the sensor receives the command to open or close the lock, it will use this interface to do so.

Appendix B: Decomposition Compiler Input

The decomposition compiler takes input from one or more XML files. The required input consists of the rule, a system definition and the system properties.

The XML files for the example in section 6.2.2 are given below.

The rule definition.

```
<rule>
	<on>
		<event> E </event>
	</on>
	<if>
		<condition> C </condition>
	</if>
	<then>
		<action> A </action>
	</then>
</rule>
```

The system definition.

```
<system>
	<systempartlist>
		<systempart> x </systempart>
		<systempart> y </systempart>
	</systempartlist>
	<communicationgraph>
		<communicationedge>
			<from> x </from>
			<to> y </to>
		</communicationedge>
		<communicationedge>
			<from> y </from>
			<to> x </to>
		</communicationedge>
	</communicationgraph>
</system>
```

The system properties definition.

```
<systemproperties>
	<capabilitylist>
		<capability systempart="x"> E </capability>
		<capability systempart="x"> C </capability>
		<capability systempart="y"> A </capability>
	</capabilitylist>
</systemproperties>
```

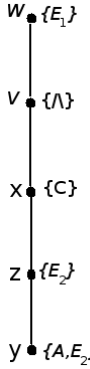
A second, more elaborate example that explains decomposition compiler usage is the following:

$R_0 = E_1 \wedge E_2 \bullet C \rightarrow A$

$L = \{v, w, x, y, z\}$

$G = \{(v, w), (v, x), (x, z), (z, y)\}$

$S = \{(v, \{'\wedge'\}), (w, \{E_1\}), (x, \{C\}), (y, \{A, E_2\}), (z, \{E_2\})\}$



The XML files for this example are:

```
<rule>
	<on>
		<and>
			<event> E1 </event>
			<event> E2 </event>
		</and>
	</on>
	<if>
		<condition> C </condition>
	</if>
	<then>
		<action> A </action>
	</then>
</rule>
```

```
<system>
	<systempartlist>
		<systempart> x </systempart>
		<systempart> y </systempart>
		<systempart> z </systempart>
		<systempart> v </systempart>
		<systempart> w </systempart>
	</systempartlist>
	<communicationgraph>
		<communicationedge>
			<from> w </from>
			<to> v </to>
		</communicationedge>
		<communicationedge>
			<from> v </from>
			<to> w </to>
		</communicationedge>
		<communicationedge>
			<from> x </from>
			<to> v </to>
		</communicationedge>
		<communicationedge>
			<from> v </from>
			<to> x </to>
		</communicationedge>
		<communicationedge>
			<from> x </from>
			<to> z </to>
		</communicationedge>
		<communicationedge>
			<from> z </from>
			<to> x </to>
		</communicationedge>
		<communicationedge>
			<from> z </from>
			<to> y </to>
		</communicationedge>
		<communicationedge>
			<from> y </from>
			<to> z </to>
		</communicationedge>
	</communicationgraph>
</system>
```

```
<systemproperties>
	<capabilitylist>
		<capability systempart="w"> E1 </capability>
		<capability systempart="v"> and </capability>
		<capability systempart="z"> E2 </capability>
		<capability systempart="x"> C </capability>
		<capability systempart="y"> A </capability>
		<capability systempart="y"> E2 </capability>
	</capabilitylist>
</systemproperties>
```

This gives the following results:

```
Decomposition 0:
v: and(Receive E1 from w, Receive E2 from x) * true -> Send and(E1, E2) to
x
```

```
w: E1 * true -> Send E1 to v
x: Receive and(E1, E2) from v * C -> Send C to z
x: Receive E2 from z * true -> Send E2 to v
y: Receive C from z * true -> A
z: Receive C from x * true -> Send C to y
z: E2 * true -> Send E2 to x
Decomposition 1:
v: and(Receive E1 from w, Receive E2 from x) * true -> Send and(E1, E2) to
x
w: E1 * true -> Send E1 to v
x: Receive and(E1, E2) from v * C -> Send C to z
x: Receive E2 from z * true -> Send E2 to v
y: Receive C from z * true -> A
y: E2 * true -> Send E2 to z
z: Receive C from x * true -> Send C to y
z: Receive E2 from y * true -> Send E2 to x
```

The XML schema definitions for the decomposition tool input are given below.
Schema for rule:

```
<xs:schema
     xmlns:xs="http://www.w3.org/2001/XMLSchema">
 <xs:simpleType name="condition">
    <xs:restriction base="xs:string">
    </xs:restriction>
  </xs:simpleType>
 <xs:simpleType name="event">
    <xs:restriction base="xs:string">
    </xs:restriction>
    <xs:attribute name="variable" type="xs:string" use="required"/>
    <xs:attribute name="type" type="xs:string" use="required"/>
  </xs:simpleType>
 <xs:simpleType name="variable">
    <xs:restriction base="xs:string">
    </xs:restriction>
    <xs:attribute name="type" type="xs:string" use="required"/>
    <xs:attribute name="source" type="xs:string" use="required"/>
  </xs:simpleType>
  <xs:complexType name="conditionfunction">
    <xs:sequence>
      <xs:choice>
        <xs:element name="condition" type="condition"/>
        <xs:element name="function" type="function"/>
        <xs:element name="variable" type="variable"/>
      </xs:choice>
    </xs:sequence>
    <xs:attribute name="name" type="xs:string" use="required"/>
    <xs:attribute name="type" type="xs:string"/>
  </xs:complexType>
  <xs:complexType name="eventfunction">
    <xs:sequence>
      <xs:choice>
        <xs:element name="event" type="event"/>
        <xs:element name="function" type="function"/>
        <xs:element name="variable" type="variable"/>
      </xs:choice>
    </xs:sequence>
    <xs:attribute name="name" type="xs:string" use="required"/>
    <xs:attribute name="type" type="xs:string"/>
  </xs:complexType>
<xs:element name="rule">
  <xs:complexType>
    <xs:sequence>
      <xs:element name = “events” >
        <xs:choice>
          <xs:element name = “function” type = “eventfunction” />
          <xs:element name = “event” type = “event” />
        </xs:choice>
      </xs:element>
      <xs:choice>
        <xs:element name = “conditions” >
          <xs:choice>
            <xs:element name = “function” type = “conditionfunction” />
            <xs:element name = “condition” type = “condition” />
```

```
          </xs:choice>
        </xs:element>
      </xs:choice>
      <xs:element name = "actions" >
        <xs:element name="action" type="xs:string"
                    minOccurs="1" maxOccurs="unbounded"/>
      </xs:element>
    </xs:sequence>
  </xs:complexType>
</xs:element>
</xs:schema>
```

Schema for system:

```
<xs:schema
     xmlns:xs="http://www.w3.org/2001/XMLSchema">
  <xs:element name="system">
  <xs:complexType>
    <xs:sequence>
      <xs:element name = "systempartlist" >
        <xs:element name = "systempart" type = "xs:string"
                    minOccurs="1" maxOccurs="unbounded"/>
      </xs:element>
      <xs:element name = "communicationgraph" >
        <xs:element name = "communicationedge"
                    minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
            <xs:sequence>
              <xs:element name = "from" type = "xs:string"/>
              <xs:element name = "to" type = "xs:string"/>
              <xs:choice>
                <xs:element name = "constraints" type = "xs:string"/>
              </xs:choice>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:element>
    </xs:sequence>
  </xs:complexType>
  </xs:element>
</xs:schema>
```

Schema for properties:

```
<xs:schema
     xmlns:xs="http://www.w3.org/2001/XMLSchema">
  <xs:element name="systemproperties">
  <xs:complexType>
    <xs:sequence>
      <xs:element name = "capabilitylist" >
        <xs:element name = "capability" type = "xs:string"
                    minOccurs="0" maxOccurs="unbounded">
          <xs:attribute name="systempart" type="xs:string" use="required"/>
        </xs:element>
      </xs:element>
      <xs:element name = "translationtable" >
        <xs:element name = "translation"
                    minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
            <xs:sequence>
              <xs:element name = "from" type = "xs:string"/>
              <xs:element name = "to" type = "xs:string"/>
            </xs:sequence>
          </xs:complexType>
        </xs:element>
      </xs:element>
    </xs:sequence>
  </xs:complexType>
  </xs:element>
</xs:schema>
```

Glossary

Abstraction level	The abstraction level of a system or a rule indicates how far the system or rule has been abstracted from an actual implementation. For a system, the lowest abstraction level is a direct one-to-one representation of the implementation. The highest abstraction level is the system as a single entity providing all the system's outside services. The abstraction level of a rule is the same as that of the system for which it defines the behaviour.
Ad Hoc network	A network between devices using wireless technology that is formed on an Ad Hoc (on the moment) basis using devices that are in immediate vicinity of each other.
Architecture	The structure of a system, comprised of its components, the properties of the components and the relationships between the components.
Context-Aware application	An application that can change its function based on context information about itself, its user, the device it is running on and/or other aspects of its environment.
Context information	Information about an entity that is not necessary for execution of a task, but allows the task to be performed in way more suitable to the user.
Context processing	The act of applying an algorithm to data originating from a context data source such as a GPS receiver, so that an application can make use of the data. Alternatively, the act of distilling higher level context data from several sources of lower level context data.
Decomposition	A transformation and division of a rule set for an abstract system into components in a rule set for a system at a lower abstraction level. See the definition in section 3.3.
Distribution	Not on a single device; non-centralized. A *Distributed Architecture* is one that consists of a number of cooperating devices that all have a role in the behaviour. A *Distributed Environment* is an environment with a number of inter-connected devices. *Distributed Computing* consists of performing parts of a task on separate devices that communicate with each other.
Middleware	Software that connects distributed software components and/or applications and supplies common functionality to these components and applications.
Rule	A business or application rule defines behaviour for a system. See the definition in section 3.1.
Rule engine	A piece of software that can execute rules based on a set of facts based on data.
System behaviour	The observable interactions that a system has with its surrounding environment.

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