University of Twente
The Netherlands

From SNMP to Web services-based network management.

Jeroen van Sloten

Thesis for a Master of Science degree in Computer Science from the University of Twente, Enschede, the Netherlands

Graduation committee:

Dr.ir. A. Pras
Dr.ir. M.J. van Sinderen

Enschede, the Netherlands
4th June 2004

Abstract

One of the emerging standards for application to application interaction and therefore for the interconnection of (distributed) systems is Web services. It is an open, generic and standardised XML-based technology and has recently received a wide industry attention. Considering the current interest of network management research groups in XML-based technologies, Web services need investigation for its suitability for network management. This is therefore the main objective of this thesis.

This thesis presents some of the characteristics of Web services that make it useful to use for network management. Furthermore, an overview of additional Web service standards that are expected to be of interest for network management is presented.

Standardisation plays an important role in the adoption of a network management technology. This thesis distinguishes which parts of a Web service are suitable for standardisation. Within these parts there is room for variation, and therefore the merits of various alternatives are discussed.

The Model-Driven Architecture (MDA) is an approach that promotes the usage of modelling for the design of (software) systems. Models should be used at different levels of abstraction, thus creating a clear separation between the specification of the functionality of a system and the implementation of this functionality on a specific platform. Since Web services can be implemented on a variety of platforms, this thesis explains why MDA can play an important role for the development of Web services in general and network management in particular.

Acknowledgements

From September 2003 to June 2004 I have carried out the final stage of my Computer Science study at the University of Twente. I have spent these nine months performing research on the use of Web services for network management, the result of which is presented in this Master's thesis.

My thanks and gratitude go to all the people from whom I have received enormous amounts of help and support while performing my research project. First and foremost I would like to thank my supervisors Aiko Pras and Marten van Sinderen, who have provided me with all the necessary help that proved valuable for this project. They have pointed me in the right direction when needed and especially they made the conversations we have had very pleasant and interesting.

Thanks also go to all my colleagues and fellow students from the ARCH group who have provided me with new insights, the necessary distraction from time to time and most of all a pleasant working environment.

Also I wish to thank my family and friends who have all been very supportive and highly inspiring, not only during my Master's project, but throughout my entire study.

And last but not least my deepest gratitude goes to Yongjun, my partner for life. She has been a great help for me, for her expertise, but especially for showing her heartfelt encouragement and continuous support. She has shown great patience while waiting for me to finish this thesis. Above all she has given me her endless love which is the greatest support of all.

Jeroen van Sloten

Enschede
June, 2004

Contents

List of Figures

List of Tables

Listings

Chapter 1

Introduction

This chapter provides an insight in the background of this research project and a detailed description of the problems that will be tackled. This is followed by an overview of the approach, related work and intended audience.

1.1 Background

Ever since the introduction of computer networks, there has been an interest in management functionality. In the early days of computer networks simple applications such as *ping* and *traceroute* were sufficient to find congestions in the network for instance. But as the complexity of networks rises and networks become more and more interconnected, the need for more complex management functionality is also growing. By the end of the eighties the development of networks and simple management tools eventually led to management standards such as the Simple Network Management Protocol (SNMP).

Since then, SNMP, in its different versions [3], has grown to be the most commonly used network management platform in IP networks. However, while originally developed in an environment where networks were small, bandwidth was scarce and processing power on networked devices was low, the design choices made then are nowadays becoming apparent limitations in the network management area.

1.1.1 Towards XML-based network management

SNMP is based on the manager-agent paradigm. For the exchange of messages SNMP relies on UDP [4], which is, according to many, a cause of great concern [5, 6]. Originally agents were meant to be as simple as possible, with most of the processing and control done at the manager-side. But times have changed and current devices are powerful enough to perform more complex management operations also at the agent side [7]. Furthermore, SNMP is a domain-specific protocol that, despite its name, is not easy to use. Integration with existing software is difficult and only a limited number of experts have sufficient knowledge to develop new management applications [7]. Because of these limitations there is nowadays a trend towards more generic technologies to be used for network management. One of the main technologies being investigated is the eXtensible Markup Language (XML) [8]. Current efforts in improving IP network management are mostly based on dedicated XML formats [9, 10].

These problems have also been the topic of discussion within the Internet Engineering Task Force (IETF) [11], the Network Management Research Group (NMRG) [12] of the Internet Research Task Force (IRTF) [13] and the Internet Architecture Board (IAB) [14]. The IAB, for example, organised a special workshop in June 2002 to discuss the future of network management (RFC3535 [15]). Many attendees at that meeting expected that the so-called evolutionary approaches would fail and that more focus should be put on revolutionary approaches, most notably approaches that are XML-based [7]. This outcome, combined with the fact that there has not been substantial output yet, has made for ongoing IETF workgroups such as Evolution of SNMP (EoS) [16] and SMING [17] to be discontinued. Meanwhile, there are even those who state that standardisation of network management protocols should move from the IETF to the World Wide Web Consortium (W3C) [18], partly because of this focus shift towards XML [19] which is a W3C standard itself.

1.1.2 Web services-based network management

An emerging standard based upon XML is Web services [20]: an open, generic and standardised technology for the interconnection of computer systems. Because it is XML-based it is in principle platform and programming language independent. One can currently notice an industry-wide interest in Web services, supported by the growing availability of various related application servers and development tools. Web services are expected to become a standard part of future operating systems and application servers, which will result in a growing familiarity among many users and developers. All these characteristics make it to be a very promising technology for (distributed) computer systems.

The availability, combined with being a generic technology and an open standard, makes it easier for people to develop applications using Web services. Apart from dedicated management applications, one can also think of presenting management information in a spreadsheet or storing management information in databases simply by calling a Web service for which support is already present in the operation system. SNMP also makes clear that availability of applications is a key factor for the market acceptance of a technology [7]. But these advantages of Web services are very general and not only relevant to network management. What is very important for network management is that there is a standardised form in which management information is defined and how this information is accessed [19]. It remains hard to develop a management application when management information and its accessor operation are not standardised.

1.1.3 Model-Driven Architecture

When legacy technologies and systems are concerned, one can think of a new concept that is rapidly evolving in the software engineering field: Model-Driven Architecture. It is proposed by the Object Management Group (OMG) [21] to bring the design of (software) systems to a higher level of abstraction than design at programming code level, by making more active use of modelling and transformations between models. MDA makes a clear separation between the specification of a system's functionality and its implementation on a particular platform [22].

The reason why this can be interesting for legacy systems is that it enables a software engineer to capture the functionality of such a system in a higher-level model. This creates an abstraction from the legacy technologies that a system is usually built on. Furthermore, with MDA it should then be possible to deploy a system with similar functionality and behaviour on a platform based on a different technology. More concretely, in case of SNMP-based network management it can be highly interesting to capture its functionality in a model that is not dependent on SNMP-based technologies.

Web services can be implemented on a variety of platforms, however some basic design issues could possibly be very similar for each platform. This is a typical area where MDA is expected to be useful.

1.2 Problem description

Since Web services is a relatively new standard, little is known about applying it for network management. There is already an interest by standardisation organisations and research groups [7] in XML-based approaches, but research thusfar focussed on dedicated XML-based approaches [9, 10], rather than generic approaches like Web services. This is why it is of great importance to acquire more knowledge on how Web services can be applied for this specific task.

Currently, XML-based Web service standards are appearing as a more generic approach towards systems interconnection. They can already be used on a wide variety of platforms (Microsoft .NET, Java platforms, etc.). Web services offer quite similar concepts as SNMP, such as invoking operations on remote systems, communication through message exchange and implementation-independent service descriptions.

Sceptics often use the argument of poor performance compared to existing SNMP implementations, when discussing Web service-based (or other XML-based) protocols [23]. It is quite obvious that XML documents can get very verbose and most certainly it is a reason for concern. However important steps in comparing SNMP and Web service performance have already been made and the results look very promising (see section 1.5.5) and are certainly reasons for doing more research in this area.

1.3 Scope and objectives

The main objective of this thesis is to investigate how Web services can be applied for network management. This makes it important to first identify a possible Web services-based management architecture and to get feeling with the concepts. The characteristics of Web services that are of particular interest for network management need to be described.

In order for a network management approach to be adopted widely, standardisation needs to take place. For Web services this means that those parts that are suitable for standardisation need to be identified. An issue related to standardisation is the definition of management operations and corresponding messages. There can be a wide variety of operations, so it is important to recognise which forms there possibly are and what the merits of each of those forms are.

Finally, applying MDA tools to aid in the development of network management Web services will be discussed. Given the fact that network management data models are standardised (for instance SNMP's data model) and the model-oriented nature of MDA, MDA could be a very useful methodology for easily developing management applications for different types of Web service-platforms.

These objectives lead to the following research questions:

- Why are Web services suitable to use for management of IP networks?
- Which parts of Web services need to be standardised for Web services-based network management?
- What possible forms can management operations take and what are their merits?
- Which role can MDA tools play for developing Web Services-based management applications?

It is **not** the intention of this thesis to do another performance comparison between SNMP and Web services, nor will it propose a gateway or dual stack solution. As mentioned before, research is already being performed in these areas. It is also not the intention to propose a new standard for network management based on Web services. Furthermore, the goal is also not to discuss the management information itself. This thesis will be based upon SNMP and therefore also the management information comprised in SNMP data models. The reader who is interested in the different data models is referred to the study presented by López de Vergara et. al. [24], which gives an interesting discussion on which management information should be available and what the best definition language is.

1.4 Approach

The following approach will be adopted in this thesis:

1. give a state of the art of SNMP, Web services and MDA. This includes the SNMP management architecture, the protocol and the data definition language. Furthermore, the concept of Web services shall be explained with a focus on the Web Services Description Language. And finally, the main concepts of the Model-Driven Architecture will be introduced.
   The goal of this step is to make the reader acquainted with the technologies that are being discussed in this thesis as well as the related terminology.
2. describe the characteristics of Web services and explain why they are suitable to perform network management.
   The goal is to understand how Web services can be applied for network management.
3. determine which parts of Web services can and need to be standardised. This will focus mainly on the description of Web services, by introducing an explanation on the modularity of WSDL documents, followed by an

elucidation on management operations.
The goal of this step is to understand which parts of a Web service can be used for network management standardisation and what variations are possible within these parts.

4. illustrate the discussed topics by means of a case study where the SNMP Host-resources MIB shall be migrated to a Web service environment. This work will be carried out by means of an MDA development tool.
The goal is to show how Web services-based network management could work in practice and to gain experience with the suitability of MDA tools in the development of Web services.

1.5 Related work

There are several initiatives in the field of network management that focus on Web services or provide very similar functionality. They will be discussed in this section.

1.5.1 Network Management Research Group

The Network Management Research Group is a small group of researchers for "*exploring new technologies for the management of the Internet*" [12]. The NMRG is a research group of the IRTF [13] and is responsible for the advances made with SNMP, SMI and other related topics after its installation in 1999.

The NMRG needs mentioning here, because of its contribution to SNMP and its current interest in investigating XML related technologies, most notably in Web services.

1.5.2 NetConf

NetConf [25] is a Working Group of the IETF [11] and chartered to produce a protocol suitable for network configuration. Configuration typically entails relatively simple tasks such as up- or downloading whole configurations. It therefore needs only a few basic operations to transfer large amounts of data. The NetConf protocol offers a small set of coarse operations to manage device configurations and retrieve device state information. However, these set of coarse operations is meant to be extensible with finer operations when specific functionality is required. But considering the expected usage of coarse operations, there is no need for standardising finer operations. Communication is performed through the exchange of NetConf-specific XML messages. Due to the wide interest in the more generic SOAP messaging (SOAP is explained in section 2.2) the NetConf WG has acknowledged that it is definitely interesting to investigate its usability for NetConf [26]. SOAP offers the functionality that is required, but more important it is widely supported on many platforms and used, almost without exception, as the message standard for Web services. NetConf could therefore possibly be used as a Web service.

1.5.3 Web-Based Enterprise Management

For the last several years, the Distributed Management Task Force [27] has been developing an information model for a managed environment, called Common Information Model [28]. CIM is an object-oriented conceptual view of the managed environment, unlike SNMP, which is a data-oriented model and protocol. The CIM does not include only some generic properties of networked devices, like many standardised SNMP MIBs, but it attempts to provide a very comprehensive and detailed view of a managed system. Naturally this results in a large collection of objects. These objects are defined textually in the Managed Object Format (MOF) [29], but are also presented in a (non-normative) graphical form.

The CIM is part of the Web-Based Enterprise Management (WBEM) initiative. WBEM is "*a set of management and Internet standard technologies developed to unify the management of enterprise computing environments*". Apart from the CIM, it also includes a protocol for transporting management data (CIM Operations over HTTP) and an encoding specification (xmlCIM Encoding Specification) that is used to represent CIM classes and instances.

1.5.4 Web Services Management Framework

Hewlett Packard [30] has developed a logical architecture for managing computing resources through Web services. This is called The Web Services Management Framework (WSMF) which is now adopted by OASIS [31]). It has been developed to address the growing need of businesses to integrate their systems, and more specifically the management of those systems. The framework provides a collection of interfaces that expose a certain type of management information for so-called managed objects. Each interface has operations that are related to a specific task, such as monitoring, discovery or configuration. The WSMF allows for interfaces to be extended and new interfaces to be added for managed objects.

The aim of the WSMF is to provide a generic, platform independent interface to management information. The operations provided by the interfaces that are standardised, are generally very fine operations which serve a specific task. The idea is to use the extensibility of Web services to specify more non-standardised operations when needed. Another idea is that, since common interfaces provide common operations, one single interface (and thus its operations) can also be used for a collection of managed objects.

1.5.5 Other

Gateway solutions

Some groups try to find solutions to incorporate SNMP with dedicated XML solutions and even already a Web services-based management approach: so-called gateway solutions. These architectures mostly consist of SNMP agents, XML-based managers and an XML to SNMP request translator. Because they are not Web service-based they will not be further discussed here, but since they cover a similar area of research they are worth mentioning as related work. Main research in this area takes place on the Pohang University of Science and Technology in South-Korea [9], the Technical University of Braunschweig in Germany [10] and the Federal University of Rio Grande do Sul in Brazil [32].

Performance

Poor performance is a commonly heard argument by critics of Web service-based network management. One important reason is that Web services are based on XML and XML documents have the tendency to get rather verbose. Currently undergoing research on the comparison of SNMP and Web services seems very promising for Web services though.

First of all, work carried out at the University of Twente [33] has focussed on comparing bandwidth and resource usage of SNMP and Web services with regard to network monitoring (management data retrieval). SNMP and Web services have been tested both with and without using data compression. The results of these comparisons are very promising as they show that Web services do not perform much worse than SNMP. In fact, in some cases it performs even better, like when large amounts of data are concerned. With small amounts of data (which is the typical usage of SNMP), SNMP does generally perform better than Web services.

Ricardo Neisse et al. [32] introduce the idea of defining operations on different levels of granularity instead of merely copying the SNMP primitives. In this SNMP to Web services gateway, operations are defined on a so-called protocol-level or on an object-level. Operations on protocol-level are translations of SNMP primitives: *Get*, *GetNext* and *Set*, whereas on the object-level there is a specific *Get* method for each scalar and table object, such as *GetSysLocation* or *GetIfTable*. A *Set* method is created for each writable object, i.e. *SetSysLocation* or *SetIfAdminStatus*. So the protocol-level gateway has a few operations with very coarse granularity, whereas the object-level gateway supports only operations with very fine granularity. The incentive of this research project was to conduct a bandwidth comparison between the gateway fine coarse operations and the gateway with fine operations. The result of this comparison was that protocol-level gateways are only interesting when just a few SNMP objects are concerned. This type of gateway uses SNMP object identifiers and the SNMP style of communication: a response message for each single value. The object-level gateway reduces network traffic, because it can send collected management information back to the manager in one SOAP message. This turns out to be more efficient with a high number of instances (this number varies for compressed or uncompressed messages and for SOAP over HTTP or over HTTPS). Therefore an object-level gateway is of particular interest for configuration management, where typically large amounts of information is transferred.

1.6 Intended audience

This report is written for computer scientists, network specialists and other people with a background in network management and more specifically SNMP. The reader is expected to have some basic understanding with concepts such as Web Services, WSDL and MDA and more profound knowledge on SNMP, MIBs and possibly SMI. These standards will be explained here rather briefly.

1.7 Structure

This report is structured according to the steps defined in the approach (section 1.4). Step 1 relates to chapter 2 that presents the state of the art of SNMP, Web services and MDA. The next step relates to chapter 3 that describes how Web services can be applied for network management. Chapter 4 identifies which parts of a Web service can be used for network management standardisation and what variations are possible within these parts. Chapter 5 illustrates several Web service concepts with a case study on the migration of the Host-resources MIB to Web services-based network management. Finally, conclusions are drawn and recommendations are given in chapter 6. This structure is depicted in figure 1.1.

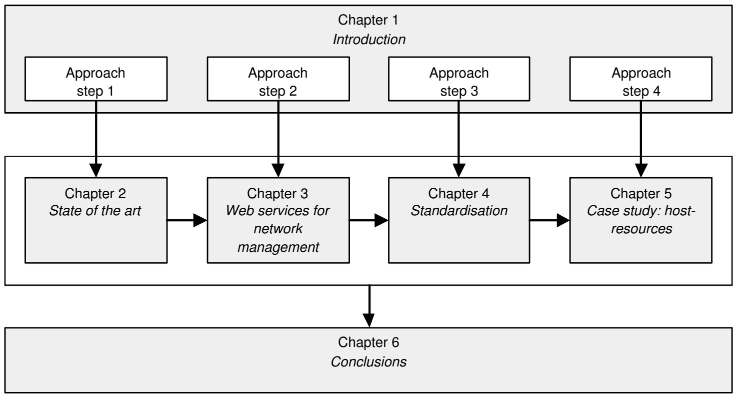


Figure 1.1: Thesis structure

Chapter 2

State of the art

This chapter presents the state of the art of the main technologies that are relevant to the research questions. Firstly, section 2.1 provides an introduction to the Simple Network Management Protocol and describes its basic concepts. Section 2.2 explains what Web services actually are and gives a detailed overview of the Web Service Description Language. This chapter concludes with section 2.3 on the Model-Driven Architecture.

2.1 Simple Network Management Protocol

2.1.1 Foundation

In the early years of small networks (roughly until the mid-eighties), small applications as *ping* and *traceroute* were powerful enough to provide basic management functionality. But with the exponential growth of networks since the late eighties, the need arose for a management protocol with much more functionality. Several approaches were evaluated and finally SNMP was selected as a short-term solution, because of its simplicity. In the long-term it was thought to make way for a different, more elaborate management protocol which was to be part of the OSI model [34].

Being a part of the TCP/IP suite, SNMP followed a similar development as TCP/IP. Both were thought to be simple and short-term solutions, as they would in the future be replaced by the OSI standards. However, since they experienced a vast deployment in rapid growing networks, both protocols outlasted their lifetimes by far. In fact, they are still widely used nowadays and the OSI models remain reference models. To date, almost all vendors of computers, bridges, routers, etc. offer SNMP support for their products.

SNMPv1 was released in 1989 followed by a proposal for version SNMPv2 in 1993 and a revision of this version in 1995. Then in 1998 SNMPv3 was issued, which experienced a big focus shift to security. It extends both SNMPv1 and SNMPv2. All of these versions are extensions of the following three foundation specifications [1, p.75]:

- Structure and Identification of Management Information for TCP/IP-based networks (RFC 1155 [35]).

- Management Information Base for Network Management of TCP/IP-based Internets: MIB-II (RFC 1213 [36]).
- Simple Network Management Protocol (RFC 1157 [37]).

2.1.2 Architecture

The SNMP network management architecture makes a clear distinction between the roles of SNMP-enabled networked devices and systems. A *management agent* is a device or system that is being managed and a *management station* is a system from which agents are managed. A management station is sometimes also referred to as a *manager*.

The architecture also defines a management protocol, that provides the link between the managers and agents. Management information itself is standardised and defined in the form of Management Information Bases (MIB). If an agent is said to support a certain MIB, the manager consequently knows how to address the agent in order to access information defined in this MIB. The overall SNMP network management architecture is depicted in figure 2.1.

Many networked devices, such as PC's, routers, printers, hubs, switches, etc. can contain an SNMP agent. A manager is the interface for a human network operator to monitor and configure these networked devices. Therefore mostly a PC or workstation contains a manager, since these are able to present a (graphical) user interface to the operator. These systems itself can also contain an agent, allowing a management application to also manage the system it is running on. Typical applications on a manager include data analysis and fault recovery. A manager could for instance also be connected to a database system, in order to periodically store management information for statistical purposes.

A management agent in its turn, is able to retrieve the actual data from the device it is running on. An agent either waits for requests from a manager, or it can initiate action by sending a so-called trap to the manager. Agents and managers are able to communicate with each other by means of SNMP primitives, as defined by the SNMP protocol. The key capabilities that these primitives offer are to *get* and *set* management information from an agent by a manager, and to send *trap* notifications from an agent to a manager. Traps are used to inform a manager of unusual events that have occurred on the agent-

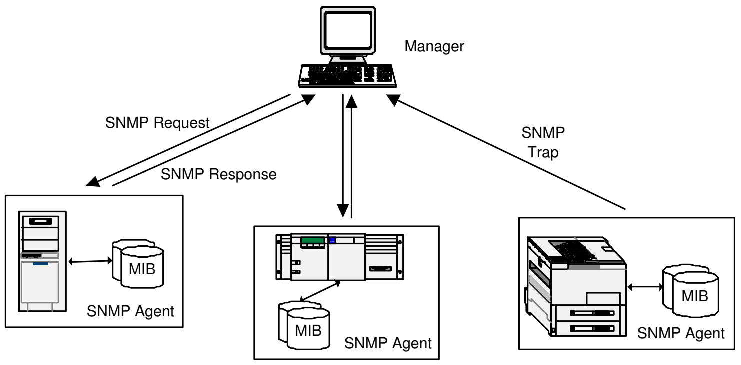


Figure 2.1: SNMP basic operation

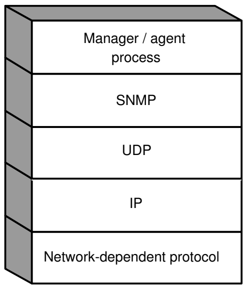


Figure 2.2: SNMP network stack

side, such as a reboot after a crash of the system, a link that is down or some pre-defined condition that is fulfilled. For instance, if the agent notices that the percentage of TCP error packets of the total amount of TCP packets is above a certain level, it can notify the manager by means of a trap.

SNMP is designed to be a part of the TCP/IP protocol suite. Its intended use is on top of the User Datagram Protocol (UDP) [4], because UDP is connectionless. This would allow a management application to be in full control of retransmission strategies, in case connections are lost or congestions have occurred [7]. Also it does not have a lot of protocol overhead. The datagram headers that need to be created are very small, compared to TCP for instance, which limits the size of the datagrams [5]. Within the IETF, there has been an attempt to use SNMP on top of TCP [38], but this is still experimental. Figure 2.2 shows examples of the SNMP protocol stack which should be existent on both a manager and an agent.

Each manager and each agent must at least implement IP, UDP and SNMP. This excludes any networked device that does not implement the TCP/IP stack from being managed by SNMP. There are provisions however, to create so-called proxy agents in order to translate SNMP requests to a different management protocol and vice versa. The SNMP agent in this case maintains the management information on behalf of one or more non-SNMP devices.

2.1.3 Management Information Base

Resources in a networked device are defined as managed objects. This concept of an object should not be confused with the concept that is commonly known from object-oriented programming. These are **not** the same. In fact, a managed object is merely a data variable representing one aspect of a resource. For example, suppose a router is a resource, then the system uptime would be one aspect of the router. Thus "system uptime" could be called a managed object in SNMP terminology.

A collection of managed objects that are in some way related to each other are grouped together in a structured format called a Management Information Base, also called a MIB module or a MIB. A formal definition of a MIB module is the following [39]:

> *"MIBs are specifications containing definitions of management information so that networked systems can be remotely monitored, configured and controlled."*

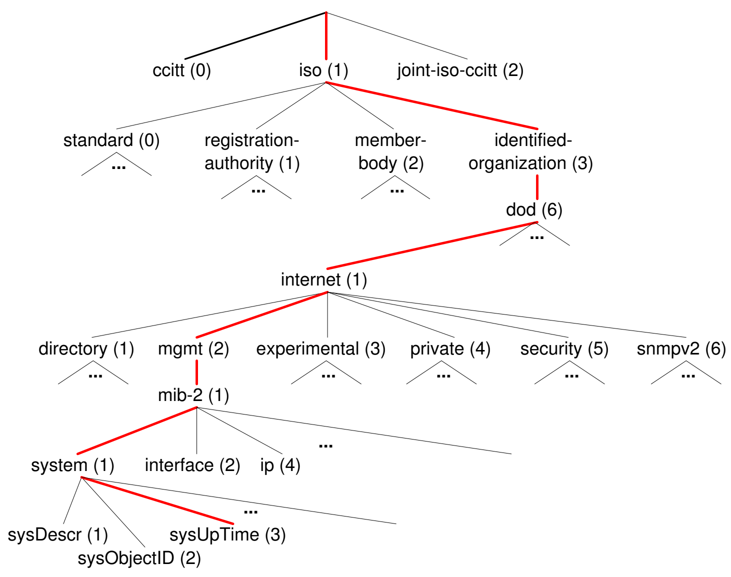


Figure 2.3: SNMP naming tree

The main objective of a MIB is to enhance interoperability across networked devices. One way this is accomplished is to have managed objects representing a particular resource the same at each system. For instance, a managed object representing the system uptime on one system, should have the same name and function on another system. It would be a great cause of confusion when, for example, one system would regard it as the time elapsed since the last reboot, and another system regards it as the time elapsed since the operating system was installed regardless of any reboots. Such a situation is not feasible of course.

A second way to enhance interoperability is to have a common definition language for the representation of MIBs: the Structure of Management Information (SMI) [35]. SMI is based on the ASN.1 notation, but uses only a very small subset of it for the sake of simplicity. SMI identifies only several basic data types and specifies how resources are represented and named. New types can be defined based on the basic types, but they can only be either scalars (based on *integer*, *octet string*, *null* or *object identifier*) or two-dimensional arrays of scalars (with *sequence* and *sequence of*). This rules out all possibilities for more complex data structures.

Managed objects are arranged hierarchically in a tree structure, where each leaf represents a managed object. All nodes and leafs in the tree are given a permanent number, so that each managed object can be uniquely identified on a single networked device by a sequence of these numbers: the object identifier (OID). This OID is defined in a MIB where the corresponding managed object is also defined. An example of (a part of) the SNMP naming tree is given in figure 2.3.

If for instance someone wants to retrieve the system uptime of a certain networked device, it has to provide the corresponding OID to the *get* primitive. The OID represents the place of the system uptime variable in the naming tree. Starting from the root, the following path should be followed to reach this

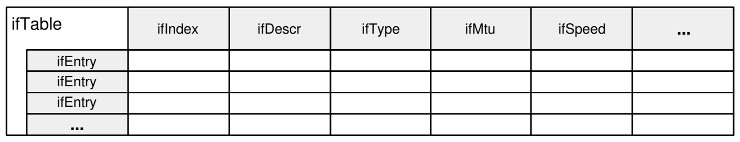


Figure 2.4: Conceptual table: *ifTable* (Interfaces MIB)

variable:

$$\texttt{iso} \rightarrow \texttt{org} \rightarrow \texttt{dod} \rightarrow \texttt{internet} \rightarrow \texttt{mgmt} \rightarrow \texttt{mib-2} \rightarrow \texttt{system} \rightarrow \texttt{sysUpTime}$$

When the names of the nodes are replaced by the node number, the following OID is retrieved:

```
1.3.6.1.2.1.1.3
```

If this OID is provided with the SNMP *get* primitive, the addressed agent retrieves this value from the system it is running on and sends it to the manager in a response message.

Two-dimensional arrays are a very simple way (in fact the only way in SMI) of structuring data. It allows for the creation of conceptual tables: they appear as tables, but they can only be addressed cell by cell. Such a table consists of instances of a certain row object-type. For example, the Interfaces MIB [40] defines an *ifEntry* object-type. *ifEntry* itself is a sequence of scalar values, which are in essence instances of simple object-types. In pseudo-code:

```
IfEntry ::= SEQUENCE {ifIndex, ifDescr, ifType,
   ifMtu, ifSpeed, ...}
```

The *ifTable* then is a sequence of instances of *ifEntry*. In pseudo-code:

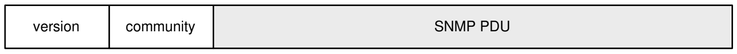
```
ifTable ::= SEQUENCE OF IfEntry
```

This creates a conceptual table, as depicted in figure 2.4. Nesting of tables is not allowed, i.e. an element of a table (or of *ifEntry* in the example) can itself not be another table. This would make a MIB overly complex and thus is chosen to allow restrictions of this kind in SMI.

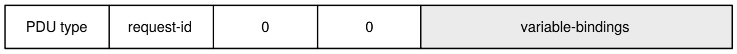
2.1.4 SNMP protocol operations

In section 2.1.2 is already briefly mentioned that agents and managers communicate with each other by means of SNMP primitives. These primitives are also referred to as protocol operations. Each operation has a corresponding message structure to comprise any parameters necessary to fulfill the operation's goal.

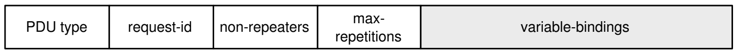
This section will discuss the message structure of the operations defined for SNMPv2 (and SNMPv3), which is a superset of SNMPv1. The original specification can be found in RFC 3416 [41] and the corresponding SMI definitions in appendix A. SNMPv2 distinguishes several operations: *get*, *get-next*, *get-bulk* and *set* are used to retrieve or modify management information on an agent by a manager. This is done by exchanging request and response messages.



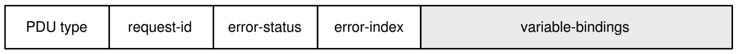
(a) SNMPv2 message structure



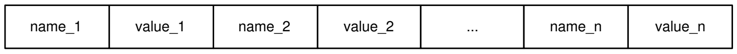
(b) GetRequest-PDU, GetNextRequest-PDU, SetRequest-PDU, SNMPv2-Trap-PDU, InformRequest-PDU



(c) GetBulkRequest-PDU



(d) Response-PDU



(e) Structure of *variable-bindings*

Figure 2.5: SNMP message and PDU formats (taken from [1]).

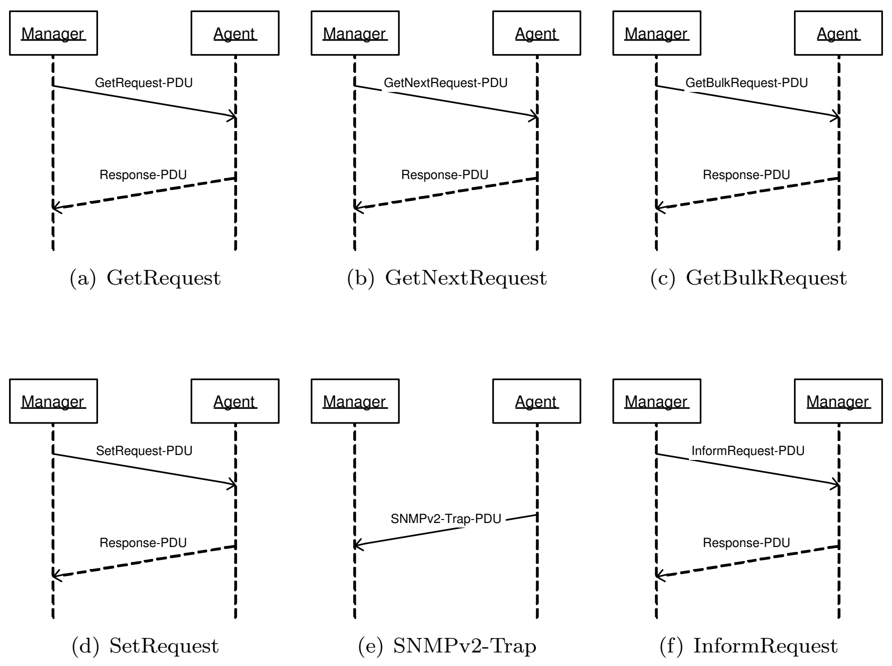
Furthermore, there is an operation *trap* that is used for agent to manager communication, usually in case some serious problem has occurred. And finally there is an operation *inform* for manager to manager communication, usually to exchange information between higher level applications.

Interaction between managers and agents takes place by the exchange of messages. Each SNMP message has a general structure. It consists of a *version* field (to denote the SNMP version), a *community* field (used for access control) and a *PDU* field. This is shown in figure 2.5(a). A PDU stands for a Protocol Data Unit and its internal structure is dependent on which operation is comprised in the SNMP message. In other words, each operation defines a PDU, that holds the operation name and its parameters and/or values.

Figure 2.6 shows the message interaction for each operation and shows the PDUs involved in each exchange. Even though PDUs can have different internal structures, they all share a *PDU type* field and a *request-id* field. The PDU type field is used to denote what kind of PDU structure follows, e.g. the Response-PDU. In case there are multiple outstanding requests, there should be a mechanism to distinguish to which request an incoming response belongs. This is done by putting a uniquely defined request-id in the corresponding field of both a request PDU and its Response-PDU. This value should be the same for each request-response pair.

It is clear from figure 2.6 that operations that require a response message all use the same PDU for it. The structure of a Response-PDU is shown in figure 2.5(d). Besides the already mentioned *PDU type* and *request-id* fields, it has an *error-status* and an *error-index* field. A non-zero value for *error-status*, means that an error has occurred and the value denotes the specific error, while the *error-index* contains the index of the variable in the *variable-bindings* list that caused the error. This will be explained later.

Most PDUs involved in a request also share a similar structure. Figure



(a) GetRequest (b) GetNextRequest (c) GetBulkRequest

(d) SetRequest (e) SNMPv2-Trap (f) InformRequest

Figure 2.6: SNMPv2 PDU sequences (taken from [1]).

2.5(b) shows the PDU format of the GetRequest-PDU, GetNextRequest-PDU, SetRequest-PDU, SNMPv2-Trap-PDU and the InformRequest-PDU. The fields that are used in the Response-PDU for *error-status* and *error-index* have a value of 0 in a request PDU. The one exception is the GetBulkRequest-PDU. Instead of the two error fields, it has a *non-repeaters* and a *max-repetitions* field. The GetBulkRequest-PDU is added to SNMP to enhance the efficiency of the GetRequest-PDU in the way it retrieves large amounts of variables. More information on this can be found in [1].

The main difference between the PDUs used for a certain operation can be found in the contents of *variable-bindings*. Its structure is depicted in figure 2.5(e). The *variable-bindings* field is a list of name-value pairs, where each name is an object identifier. Depending on the type of PDU, the value is an object instance value, unspecified, noSuchObject, noSuchInstance or endOfMibView.

For example, a *get* request will only hold the names of the variables and each value field should in all cases be set to *unspecified*. The value fields should contain the values for each requested variable in the response (unless some error has occurred, then it is replaced by noSuchObject, noSuchInstance or endOfMibView). However, the *set* operation will contain the values already in its request PDU, since they will be used for modifying the values in an agent. The result of this operation is then put in the Response-PDU.

Finally, it is worth mentioning that the Protocol Operations for SNMPv2 specification (RFC 3416 [41]) defines one more operation: report. The corresponding PDU would be the Report-PDU, however the usage and semantics of this operation are not defined and therefore it will not be discussed in this thesis.

2.2 Web Services

2.2.1 Basic concepts

Many people will nowadays regard the Web as a large collection of web sites, web portals and all other kinds of information displays. Most certainly this is and will remain a very important aspect of the Internet. However, the machine-aware part of the Internet is becoming increasingly important, for it is currently under heavy development and the technologies look promising. The machine-aware part referred to is called Web services for which the World Wide Web Consortium gives the following definition [42]:

> *"A Web service is a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format (specifically WSDL). Other systems interact with the Web service in a manner prescribed by its description using SOAP-messages, typically conveyed using HTTP with an XML serialisation in conjunction with other Web-related standards".*

Simply said, Web services make it possible for machines to communicate with each other regardless of specific hardware or software that a machine uses. Of course, the only requirement is that a machine is able to process Web service requests and responses.

The idea behind a Web service is that an application can easily make use of operations that are not implemented on the system where it is running on. This could be useful in case functionality is offered that can not easily be implemented on each system, such as access to specific information or from a certain company. Figure 2.7 shows an example of a Weather service that is provided through a Web service interface. In principle all PC's, mobile phones and other platforms that can send Web service requests are able to communicate with this Weather service and are therefore able to use weather information in their applications. A possible request could for instance be:

```
tempRequest( "Amsterdam" )
```

This would return the current temperature in degrees Celsius in Amsterdam by means of the following response:

```
tempResponse( "26" )
```

The possible kinds of requests are of course dependent on what is implemented on the server-side.

Web services commonly communicate through the exchange of Simple Object Access Protocol (SOAP) messages [43]. SOAP is a standardised form of XML messages, language and platform independent and it allows programs to communicate through standard application protocols, such as HTTP [44], FTP [45] or SMTP [46]. However, Web service communication is not limited to SOAP only. One can for instance also use HTTP-GET or HTTP-POST messages, instead of SOAP messages. Figure 2.8 depicts a Web service that exposes two endpoints. Each endpoint can define a different way of accessing the same service (e.g. SOAP or HTTP-GET).

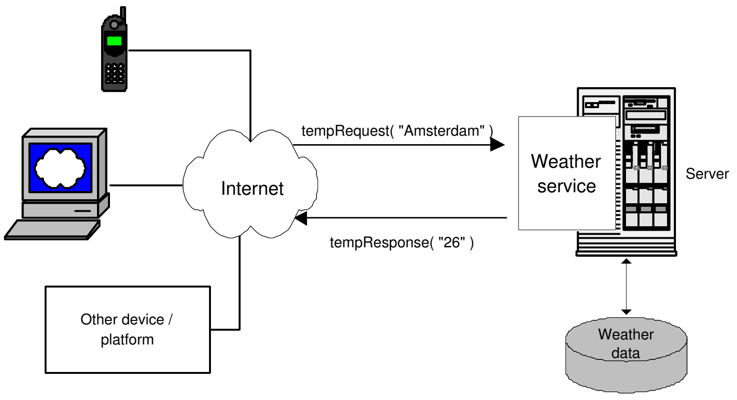


Figure 2.7: Web service: weather service

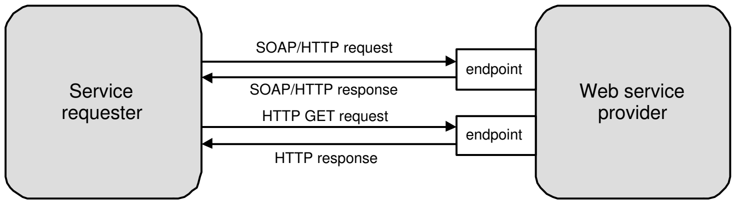
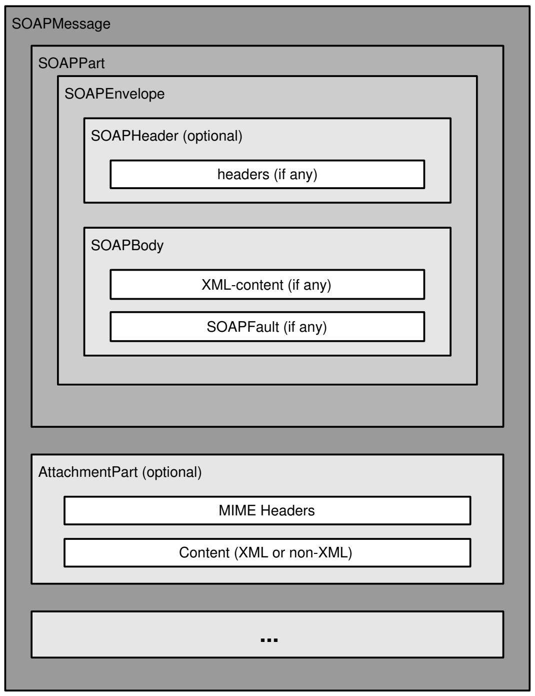


Figure 2.8: Web services communication

There are several characteristics of Web services that make them particularly interesting to use in a distributed environment: they are standardised, extensible and discoverable. Standardisation is mainly concerned with the parts of a Web service that the "outside world" can have a notion of, such as the interface and the messages. The interfaces are described in a WSDL document, which shall be explained in more detail in section 2.2.2. SOAP messages are the most commonly used message format for Web services and subject to continuing standardisation as well. Having open standards such as these, make it relatively easy to develop Web service tools and applications.

Web services are by design highly extensible. WSDL documents can be very simple, using basic elements and data-types (most commonly XML Schema [47] types), but they can also be defined in a modular manner, distributed to any extend and using self-defined data-types of any complexity. SOAP also defines a basic message structure, which can be extended with (extra) headers, attachments and fault messages. An example of the SOAP message structure can be found in figure 2.9, which also shows the optional (thus extensible) parts.

An interesting feature and necessary of Web services is the discovery service. Before a Web service can be used it needs to be discovered, either at design time or at runtime. Also it is easy to imagine that, with a vast amount of available Web services, it is difficult to find a particular Web service that serves one's needs. One way to tackle this problem, is the definition of a discovery service.



source: The Java Web Services Tutorial 1.0

Figure 2.9: SOAP message structure

One approach that is tightly linked to Web services is Universal Description, Discovery and Integration (UDDI). The OASIS UDDI Technical Committee [48] gives the following goal of UDDI:

> *"UDDI specifications form the necessary technical foundation for publication and discovery of Web services implementations both within and between enterprises".*

Discovery forms a very important part of the Web services architecture. Figure 2.10 provides a schematic overview of the architecture and the relations between a service provider, a service requester and the UDDI server.

In the past there have been similar approaches to provide coupling between applications, such as XML-RPC [49], CORBA [50], Java RMI [51] and similar technologies. But these are either very extensive in functionality (CORBA) having only few people familiar with it, not standardised by industry agreement (RMI) or rather ad hoc by nature. Web services seem to gain a lot of industry support, according to the involvement of companies such as Microsoft (.NET Web services) [52], IBM (Websphere Application Server) [53], HP (Web Services Management Framework) [30], SUN (Java Web Services Developer Pack) [54], Novell (Novell exteNd) [55], BEA Systems (WebLogic Server) [56] and organisations such as Apache (Axis and the Jakarta Tomcat server) [57].

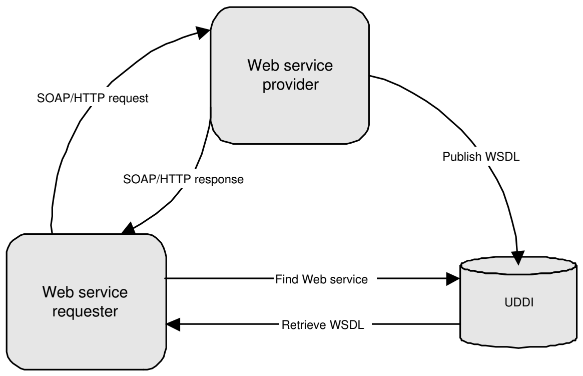


Figure 2.10: Web services architecture

2.2.2 Web Service Description Language

A Web service is described in a Web Service Description Language (WSDL) definition [58], which is an XML-based standard. A WSDL document defines the operations, which messages are used for an operations , via which protocols (SOAP, HTTP, etc.) an operation can be accessed and on which location (i.e. the IP number or domainname) the Web service resides.

For the explanation of the most important WSDL elements, definitions from WSDL version 2.0 will be used. The main differences with the previous version (1.1) is that operation overloading has been removed, the element `<porttype>` is now called `<interface>` and `<port>` is now called `<endpoint>`. An example of a WSDL document is shown in listing 2.1. This lists the main elements and shows the relation between them.

A WSDL document has `<definitions>` as root element. Namespaces can be defined as attributes of this element. Each Web service is defined by means of a `<service>` element and can be accessed through endpoints. An `<endpoint>` specifies at which address this particular service can be accessed and which protocol should be used for that. Suppose a Web service can be accessed using both HTTP GET messages and SOAP messages over HTTP, the locations of both endpoints need not necessarily be the same. Listing 2.1 shows that the *connectionManagementService* can be accessed only with SOAP at location "http://example.com/cms". If this service can also be accessed with HTTP GET messages, it should have a second endpoint such as in listing 2.2 which also shows how the location of each endpoint can be different.

An interface exposes the operations of the Web service. This can be compared to a function library or a class in a common programming language. Within an operation one can define what the input and output messages are with the `<input>` and `<output>` elements. Each of these elements corresponds to a (SOAP) message exchanged between the client and the service. The structure of such a message is defined in a `<message>` element to which the input or output refers. A message can be split up in several parts, each described by a `<part>` element. Each part has a certain data-type (most commonly XML Schema types). However, types can also be described at WSDL level by means of the `<types>` element.

An `<interface>` contains abstract descriptions of the Web service opera-

```
<definitions
  xmlns="http://schemas.xmlsoap.org/wsdl/"
  xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
  xmlns:http="http://schemas.xmlsoap.org/wsdl/http/"
  xmlns:xs="http://www.w3.org/2001/XMLSchema"
  xmlns:soapenc="http://schemas.xmlsoap.org/soap/encoding/">

  <types />

  <message name="getNumberOfTcpConnsRequest">
    <part name="index" type="xs:int"/>
  </message>

  <message name="getNumberOfTcpConnsResponse">
    <part name="tcpconns" type="xs:int"/>
  </message>

  <interface name="cmsStatistics">
    <operation name="getNumberOfTcpConns">
      <input message="getNumberOfTcpConnsRequest"/>
      <output message="getNumberOfTcpConnsResponse"/>
    </operation>
  </interface>

  <binding name="cmsSoapBinding" type="cmsStatistics">
    <soap:binding style="rpc"
        transport="http://schemas.xmlsoap.org/soap/http"/>
    <operation name="getNumberOfTcpConns">
      <soap:operation soapAction="http://example.com/cms/getNumberOfTcpConns"/>
      <input>
        <soap:body use="literal"/>
      </input>
      <output>
        <soap:body use="encoded" namespace="http://example.com/cms/message/"
            encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
      </output>
    </operation>
  </binding>

  <service name="connectionManagementService">
    <endpoint name="cmsSOAP" binding="cmsSoapBinding">
      <soap:address location="http://example.com/cms"/>
    </endpoint>
  </service>

</definitions>
```

Listing 2.1: WSDL example

```
<service name="connectionManagementService">
  <endpoint name="cmsSOAP" binding="cmsSoapBinding">
    <soap:address location="http://example.com/cms"/>
  </endpoint>
  <endpoint name="cmsHTTP" binding="cmsHttpGetBinding">
    <http:address location="http://example2.com/cms"/>
  </endpoint>
</service>
```

Listing 2.2: Endpoints

tions while a `<service>` element more concretely describes where this interface is located, i.e. the server address is defined here. Listing 2.2 shows how two endpoints reside on two different servers.

The mapping of the interface to a location is done with a binding. A binding specifies what kind of messages are exchanged and in which style. In the example SOAP messages are used over HTTP, which is defined in the `<soap:binding/>` element. For each message that is defined in the interface, the binding specifies how the contents should be interpreted: the encoding.

2.3 Model-Driven Architecture

2.3.1 Introduction

Over the last decade the Object Management Group (OMG) [21] has been involved in developing specifications and standards in order to support the development of (distributed) systems. Two of their main achievements are the standardisation of an Object Request Broker as part of the Common ORB Architecture (CORBA) [50] and later the development and standardisation of the object modelling language UML (Unified Modelling Language) [59].

Unfortunately, to date UML is mostly used for informal modelling: describing some basic functionality or concepts of the system under development [60]. The reason for using UML is that it is by now widely understood by many software engineers and UML notations have very specific meanings that should leave no room for different interpretations. Informal models, be it in (partial) UML or in a natural language (English), can not be used for code generation or dynamic execution models. This requires precise (computational complete) models, which then requires more time and effort be put in (UML) modelling.

Sometimes modelling a system or application is not even always done before implementation starts [61]. Therefore, to promote the usage of modelling, and mostly formal modelling, the OMG has adopted a new framework for software engineering: Model-Driven Architecture (MDA), which they call "*just another evolutionary step in the development of the software field*" [62]. Unlike for instance CORBA, MDA is not a framework for the implementation of distributed systems, but rather an approach to using models in software engineering in order to ensure interoperability, portability and reusability. In an increasingly integrated environment where technologies keep evolving and new "hot" technologies arrive each 18 months or so, it is ever more important to develop applications that outlast the technologies they are based on.

Nowadays, technologies typically evolve much faster than applications that make use of them. Therefore either new technologies have to be concerned with being backwards compatible, or applications need to be altered and fit for an updated or new technology. This last part is the most interesting part and a focus area of MDA technology. Even though the logic of an application does not change, it may still need to be adjusted to adhere to a new technology. All together, this stresses the need for fully-specified platform-independent models, including their behaviour.

2.3.2 Basic concepts

Modelling

The two basic concepts of MDA are models and metamodels. A model is a representation of a part of the function, structure and/or behaviour of a system [63]. If the system is a house, a model can be its architectural blueprint, if it is a software application, a model can be a collection of UML diagrams. A metamodel can be explained as being a set of the constructs/rules for creating a model.

With the use of metamodels, 3 levels of model abstraction can be distinguished: the model itself (level M1), instances of the model (level M0) and the metamodel level (level M2). For example, suppose a system is modelled using UML diagrams, then level M1 represents these diagrams. Level M0 is the implementation of these diagrams, i.e. the objects/classes written in a certain programming language. Level M2 should then be seen as a language that defines the constructs of UML diagrams and the rules that can be applied in each diagram.

M3	MOF	(meta-metamodel)
M2	UML, IDL, etc.	(MOF metamodels)
M1	UML models, IDL interfaces, etc.	(models/metadata)
M0	Objects	(instance data)

Table 2.1: Model level hierarchy (taken from [2]).

The Meta-Object Facility (MOF) [64] defines (using its own constructs) a small set of constructs, which can be extended by composition and inheritance in order to define a model that contains richer constructs and rules. In other words, MOF constructs can be used to define metamodels such as the UML metamodel. That means that MOF is in fact a meta-metamodel and can be referred to as level M3. Level M0 to M3 with examples of possible models are depicted in table 2.1.

System design

The basic idea of MDA is to model a complete system, by comprising different aspects of that system in separate models. The set of all models should then describe the complete system. The design of a system is usually split up in parts using certain abstraction criteria, such as viewpoints or abstraction levels [22].

When a system is decomposed in different abstraction levels, the concepts of abstraction and refinement are used. Abstraction is the act of omitting irrelevant details in a model in order to obtain a simpler view on the system. Refinement is exactly the opposite: adding more detail to a model in order to obtain a more complex, yet concrete, view on the system. Figure 2.11 gives an idea of a model hierarchy that is created this way.

Furthermore, MDA identifies three main viewpoints on a system, all of which focus on distinguishing specific issues that are of concern for that system. The Computation Independent Viewpoint focuses on the environment of a system and its requirements, regarding the inner structure as transparent and keep-

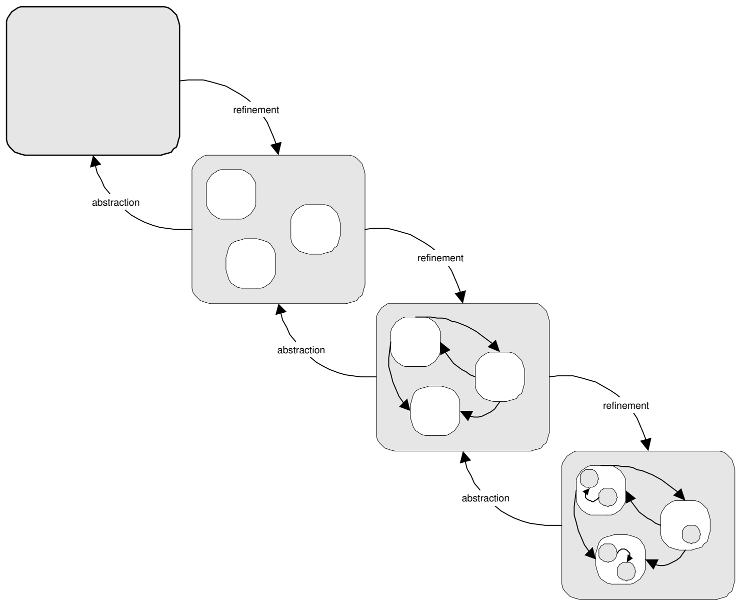


Figure 2.11: Modelling abstraction levels

ing the detail hidden. The Platform Independent Viewpoint does focus on the inner structure of a system, but in a platform-independent manner. This viewpoint shows the operation of the system in details that will not change from one platform to another. Finally, the Platform Specific Viewpoint combines the platform-independent view with platform-specific details. Examples of platforms include operating systems (Microsoft Windows, Linux, MacOS, etc.) and middleware platforms (CORBA, Web services, .NET, etc.) [22]. For completeness should be mentioned that MDA is not limited to these three viewpoints only, and where necessary other viewpoints can and should be used.

These three viewpoints have corresponding models: the Computation Independent Model (CIM), the Platform Independent Model (PIM) and the Platform Specific Model (PSM). All of them can be specified or defined in their own specific modelling language, be it a formal (graphical) modelling language like UML or plain natural language.

A CIM does not show any details of the internal structure or implementation of systems. It can be regarded as a requirements specification of a system. It should also show how the system will behave in its environment, i.e. what the system is expected to do. Typically, a CIM does not expose any platform specific details. A PIM gives a view on the internals of a system, without going into detail on the implementation issues for a particular system. Of course, generally a model can not be kept independent from all platforms that exist now and will be developed in the future. So normally a PIM will be developed with a number of platforms of a similar type in mind. Abstraction is then realised by specifying the system's internal structure in, for these platforms, general terms. Finally a PSM combines this PIM with detail of a specific platform, thereby making it clear how the system will make use of this particular platform.

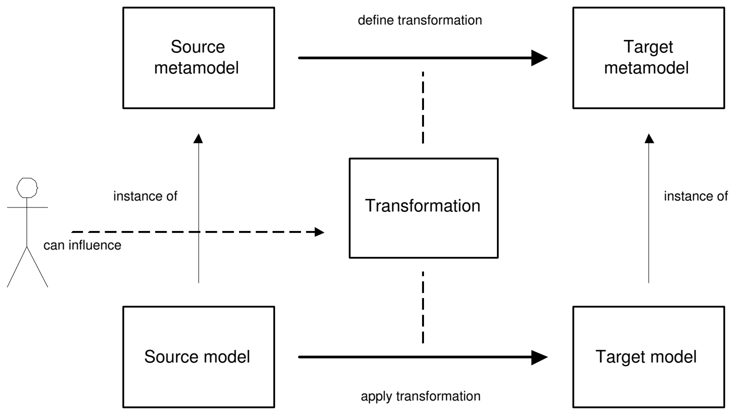


Figure 2.12: MDA model transformation

2.3.3 Model transformation

One of the main ideas of MDA is model transformation: "*the process of converting one model to another model of the same system*" [62]. Model transformation shows the real strength of MDA, namely the ability to support a system throughout its entire lifetime and not throughout the lifetime of the platform(s) it is based on [22]. Suppose new platforms arrive in the future on which systems are required to work as well. All that needs to be done is defining a suitable mapping for the system onto that new platform and each model can be transformed to those as well. Apart from reducing cost and effort of deploying a system on multiple existing platforms, it eventually should also reduce the cost of porting software to future platforms.

This is an example of a PIM to PSM transformation, sometimes also referred to as a mapping. But model transformation is not limited to this kind of mapping alone. A PIM can be transformed to another PIM, to refine certain aspects of a model without introducing platform specific details. Conversely, it can also be used to abstract from certain details. PSM to PSM transformations can be used in a similar manner, namely to abstract or refine models targeted for a specific platform. Finally it can also be interesting to have PSM to PIM transformations, for instance in case of reverse engineering. It is an effort to abstract from platform specific details, resulting in a PIM, which could then be deployed on different platforms using some mapping. The idea of model transformation is depicted in figure 2.12.

Depending on the transformation model that is used, it may be necessary to provide additional information to aid the process of generating a target model. The transformation process can be influenced by defining model markings or specifying transformation parameters. Model marking is the act of applying marks to the source model, which describe how certain model elements should be translated to elements in the target model. Therefore marks may contain certain platform specific details. Transformation parameterisation is a possibility for a user to influence a particular transformation, for instance to make certain design decisions explicit in the target model. These parameters generally apply to a certain transformation only and could be different for transformation of a different source model.

Model transformations can prove to be highly useful when the transformation process is automated, using a certain MDA tool. An MDA tool should therefore allow models to be marked or transformations to be parameterised. For very common transformations, tools could already be provided with generic transformation models, like code generators.

Chapter 3

Web services for network management

One of the incentives of this thesis is the expectancy of the Web services infrastructure to become widely available in future operating systems and developing platforms. Currently, this trend can already be noticed in the software development area where many tools are already prepared for the design of Web services. This means that many people will become acquainted with Web services and its applications. This is a big contrast with the domain specific SNMP protocol and architecture. Of course network management will remain a rather specific domain, but with applying generic technologies it will hopefully be easier understood and increasingly used.

Section 3.1 will describe how Web services can be applied to perform network management. Pre-defined message exchange patterns seem very helpful in defining an operation's messages. Interface extensibility may prove its usefulness when additional operations need to be exposed in standardised interfaces. These topics are discussed in section 3.2 and 3.3 respectively. Finally, apart from the Web services basic standards, there are many efforts to offer additional features on top of Web services. Some interesting additional efforts will be mentioned in section 3.4.

3.1 Performing network management with Web services

Web services and SNMP share very similar concepts with regard to the way communication between entities is done. Messages containing request or response information are exchanged, they are of a certain pre-defined format, operations are invoked on one side of the communication line, and performed on the other side. But whereas SNMP is solely used for network management, Web services can be used for any kind of message exchange, or remote operation invocation. This very difference is a key incentive in performing research in the usefulness of Web services for network management.

SNMP network management is based on the manager-agent paradigm: networked devices that are being managed all have an SNMP agent running,

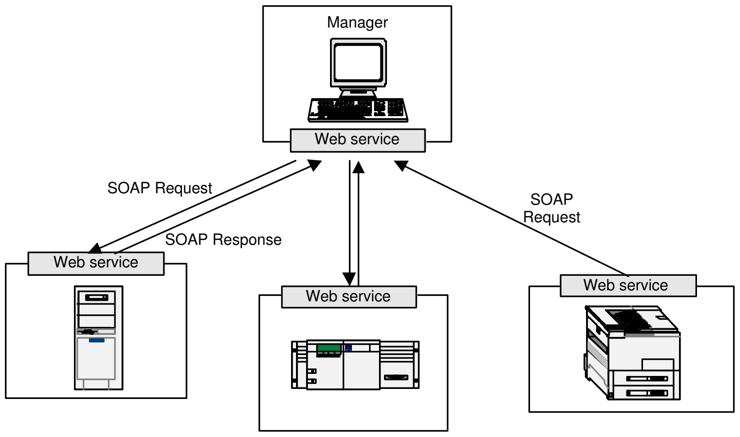


Figure 3.1: Principle operation of WS-based network management

whereas a manager is usually installed on one or more workstations, having a user interface to allow a network administrator to perform network management. The manager is able to send requests to and handle responses from these SNMP agents. When Web services are applied, the agent-side will be referred to as the service provider and the manager-side as the service requester. This entails that each networked device will contain a certain web server, capable of handling Web services. The principle operation is depicted in figure 3.1.

SNMP agents are commonly able to send traps or notifications to a manager. For Web services this would result in a situation where a service provider should also be able to play the role of service requester, and invoke operations on the manager-side. The manager will then act as a service provider instead of requester. This leads to the situation where both the agent and the manager can be a service requester or provider, and that both should contain a Web service (HTTP) server and a Web service (HTTP) client. This situation has also been distinguished in [7].

As explained in section 2.2 Web services most commonly make use of SOAP messages for its message exchange, although SOAP is not mandatory. For clarity purposes, SOAP messages are used as the preferred message standard in this thesis. The structure of the body of a SOAP message is defined in a WSDL document and the operations define which particular SOAP messages are involved in the communication process. This message structure does not necessarily need to match the SNMP messages, especially since SOAP and WSDL could make way for richer message structures. For instance, compound structures could be defined to easily transfer complete tables, or perhaps even whole configurations.

With regard to operations, it is explained in section 2.1 that for SNMP a small set of generic operations was standardised. It is possible to map these operations directly onto WSDL operations, but Web services may provide a richer set of operations. Whether this is feasible or not remains to be seen and could likely be the topic of more research. Section 4.2 provides an overview of possible forms of operations in case of operation standardisation. WSDL provides a mechanism for the extension of interfaces with operations, that may provide valuable when standardised operations do not fulfill particular needs.

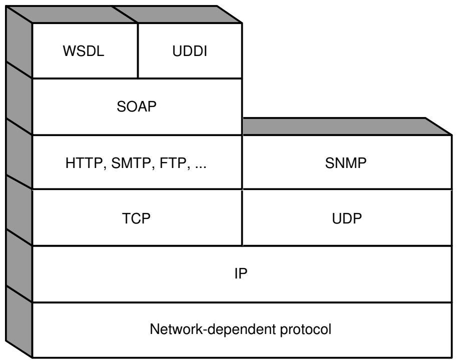


Figure 3.2: Simplified network layer stack

More on this in section 3.3.

The fact that SNMP relies on UDP for its message exchange is a cause of some concern [5, 6]. UDP is a connectionless and unacknowledged transport protocol, meaning that messages are sent to a receiver in a best-effort way. It has no way of verifying that a packet has reached its destination, nor can a sender guarantee that packets will arrive in the right order. It is therefore also known as an unreliable protocol. Any verification or retransmission should be done in applications that are using UDP.

Web services are meant to be used on top of higher-layer (application layer in the TCP/IP stack) protocols, such as HTTP, SMTP or FTP. Figure 3.2 depicts a simple network layer stack, which shows the position of both WSDL/UDDI towards SNMP. It shows that eventually Web services use TCP [65] for packet transportation. In contrast with UDP, TCP is a reliable and connection-oriented protocol. It has mechanisms for retransmission and makes sure data arrives undamaged and in the right order. Therefore when Web services are used over TCP, in principle one can be sure that messages arrive at its destination without errors. There are exceptions, for instance when a message is transferred over multi-hop networks, including intermediaries that can inspect and process SOAP headers.

What remains a question is which kind of functionality is required or feasible for network management. For SNMP the choice for UDP was deliberate: when management messages are sent in a best-effort way while there is a network congestion, it is likely that at least some messages will arrive. This makes at least some form of management possible, be it rather difficult. With TCP on the other hand, the connection needs to be set up first and packets need confirmation to keep the protocol reliable. This results in sending more packets over a network for the same management message (request-response), making management even more difficult and less likely to be possible in case of congestion. On the other hand, when transferring large amounts of data TCP could be more efficient. In case much data is transferred with TCP, it is divided over a number of packets. If an error occurs in a single packet, TCP is able to detect that, takes care of retransmission of this packet and puts all packets together in the right order. With UDP this is not possible. If one datagram is damaged, all other datagrams also need to be retransmitted. Probably experience with Web services needs to show whether TCP is suitable for network management or not. It could prove to be useful to test the performance of Web service in a congested network, or with heavy noise on the cable resulting in a high error-rate.

3.2 Message exchange patterns

An interesting part of the WSDL standard is that it provides an accompanying standard for the definition of so-called message exchange patterns (MEP) or simply message patterns. These patterns **may** be applied to operations exposed by Web service interfaces. For each particular operation they define which message interactions can take place between a Web service provider and a service requester. A pattern also defines the type of messages (normal or fault) and in which direction these messages are sent (from or to the service provider).

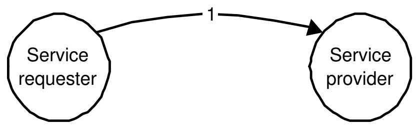
As mentioned in section 2.1 SNMP distinguishes two types of interaction patterns: request-response and trap/notification. These patterns explain how interaction between an SNMP manager and an SNMP agent can take place: a manager sends a request message to an agent and receives a response message in return (two-way), or an agent sends a trap message to the manager (one-way). SNMPv2 also defines manager to manager interaction by means of the notification primitive, which works like a confirmed trap (two-way, but service provider initiated).

With regard to Web services, such patterns can be defined in a WSDL document. WSDL version 2.0 part 2 [66] provides the definition of so-called message patterns, which extend the simple request-response and notification patterns known from SNMP as well as the SNMP-like patterns from WSDL 1.1 (one-way, request-response, solicit-response, notification). These WSDL message patterns also include fault generation rules: for each message pattern is defined whether or not it can trigger any fault messages, and the kind of fault message.

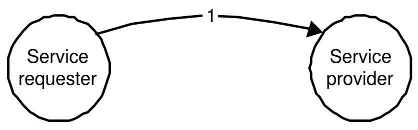
Message pattern	**Interaction pattern**	**Fault rule**
In-Only	Figure 3.3(a)	No Faults
Robust In-Only	Figure 3.3(b)	Message Triggers Faults
In-Out	Figure 3.3(c)	Fault Replaces Message
In-Optional-Out	Figure 3.3(d)	Message Triggers Fault
Out-Only	Figure 3.3(e)	No Faults
Robust Out-Only	Figure 3.3(f)	Message Triggers Faults
Out-In	Figure 3.3(g)	Fault Replaces Message
Out-Optional-In	Figure 3.3(h)	Message Triggers Faults

Table 3.1: WSDL 2.0 message exchange patterns.

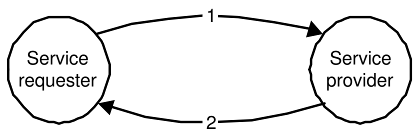
Table 3.1 gives an overview of the nine message patterns, each referring to figure 3.3 which shows how interaction takes place for each message pattern. The fault rules of the last column specify how fault messages relate to the message pattern. There are three types of fault rules distinguished: *No Faults*, *Message Triggers Faults* and *Fault Replaces Message*. As its name already implies, *No Faults* means that no fault messages may be generated. Suppose the message pattern of an operation from a service provider is defined as *In-Only*, such as in listing 3.1. If this operation is called and an error occurs on the service provider



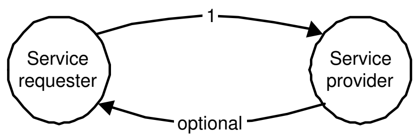
(a) In-Only



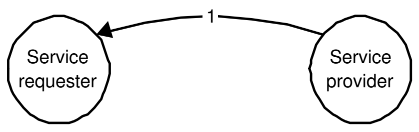
(b) Robust In-Only



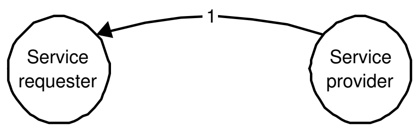
(c) In-Out



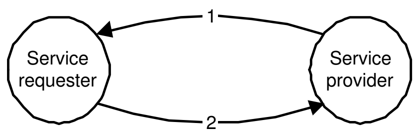
(d) In-Optional-Out



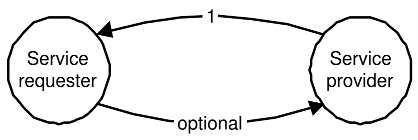
(e) Out-Only



(f) Robust Out-Only



(g) Out-In



(h) Out-Optional-In

Figure 3.3: WSDL message exchange patterns.

```
<interface name="fooInterface">
  <operation name="fooOperation" pattern="http://www.w3.org/2004/03/wsdl/in−only">
    <input message="fooInput"/>
  </operation>
</interface>
```

Listing 3.1: MEP: In-Only

```
<interface name="fooInterface">
  <operation name="fooOperation" pattern="http://www.w3.org/2004/03/wsdl/robust−in−
        only">
    <input message="fooInput"/>
    <outfault messageLabel="fooOutFault"/>
  </operation>
</interface>
```

Listing 3.2: MEP: Robust In-Only

side, the service requester should not be notified of this in a fault message. If delivering of fault messages is feasible, a *Robust In-Only* message pattern should be used, which has the fault rule *Message Triggers Faults*. This message pattern is similar to *In-Only* with the difference being the ability to return a fault message to the originator, as shown in listing 3.2.

The following definition for *Message Triggers Faults* is provided by the WSDL 2.0 specification [58]:

> *"For the pattern **message-triggers-fault**, the message that the fault relates to identifies the message after which the indicated fault may occur, in the opposite direction of the referred to message. That is, the fault message will travel in the **opposite** direction of the message it comes after in the pattern."*.

It also provides the following definition of *Fault Replaces Message*:

> *"For the pattern **fault-replaces-message**, the message that the fault relates to identifies the message **in place of which** the declared fault message will occur. Thus, the fault message will travel in the **same** direction as the message it replaces in the pattern."*.

An example of this last fault generation rule is the *In-Out* message pattern. Using this pattern, the normal way of interaction would be that upon receiving a message from the requester, the service provider would return a message to it. However, in case of an error at the provider side, the output message will not be returned. Instead, a fault message is generated and replaces the normal output message. An example of this is shown in listing 3.3.

Message patterns that start with an initiating message from a service provider to a requester, are variants of what sometimes is also called the publish-subscribe paradigm. Service requesters subscribe to a certain service from a provider, enabling this provider to send each requester a message whenever a certain event has occurred, like for instance when new information has become available [67]. WSDL even allows for the requester to send response or fault messages back to the service provider.

The above message patterns provides a greater variety of interaction patterns compared to SNMP . The request-response and trap interaction patterns from

```
<interface name="fooInterface">
  <operation name="fooOperation" pattern="http://www.w3.org/2004/03/wsdl/in−out">
    <input message="fooInput"/>
    <output message="fooOutput"/>
    <outfault messageLabel="fooOutFault"/>
  </operation>
</interface>
```

Listing 3.3: MEP: In-Out

SNMP can best be compared with the message patterns *In-Out* and *Out-Only* from WSDL. In normal operation an SNMP manager sends a request to an SNMP agent and receives a response message. If an error has occurred on the agent with processing the request, this is send to the manager as response. This is an example of *Fault Replaces Message* and thus the *In-Out* pattern. Traps are sent from an agent to a manager, which clearly corresponds to the *Out-Only* pattern, since the manager can not be triggered to return a fault message to the agent.

3.3 Interface extensibility

In the following chapter issues with regard to standardisation of WSDL interfaces, operations, messages, etc. for network management are being discussed in detail. This section will explain how WSDL interfaces can be extended with more operations. This can prove to be very useful, for instance when certain Web service operations have been standardised, but a vendor would like to provide extra, proprietary management operations. Both NetConf and the WSMF provide this functionality as well (see section 1.5).

Extensibility of an interface is the possibility for an interface to extend one or more other interfaces. In that case an interface exposes all operations of the interfaces it extends, along with any operations it defines. The only restriction is that the extended interfaces themselves can not extend the interface that is used for extending, because that would create a loop. For example, interface A can extend interface B, but then interface B is prohibited to extend interface A.

interface	**exposed operations**
intf1	op1, ...
intf2	op2, ...
intf3	op1, op3, ...
intf4	op1, op2, op4, ...

Table 3.2: Interface extension.

Interface extension can be achieved in WSDL by using the attribute *extends* for the `<interface>` element, with its value pointing to one or more other interfaces. To illustrate this mechanism, consider the interfaces *intf1* and *intf2* that expose the operations *op1* and *op2* respectively from listing 3.4. Interface *intf3* shows how interface *intf3* is extended and thus exposes the operations *op1* and *op3*, as is also shown in table 3.2. Furthermore *intf4* extends both *intf1* and *intf2*, thereby exposing the operations *op1*, *op2* and *op4*.

```
<interface name="intf1">
  <operation name="op1" ... />
  ...
</interface>

<interface name="intf2">
  <operation name="op2" ... />
  ...
</interface>

<interface name="intf3" extends="intf1">
  <operation name="op3" ... />
  ...
</interface>

<interface name="intf4" extends="intf1␣intf2">
  <operation name="op4" ... />
  ...
</interface>
```

Listing 3.4: Interface extension

3.4 Additional Web service standards

Apart from SOAP and WSDL, which can be considered the basic standards, there are many additional efforts, proposals and standards that offer some specific functionality, such as for transactions, security, reliability, etc. These efforts tackle many common issues with regard to distributed systems, and therefore inherently also for issues with network management. Since they are quite large in number and generally rapidly evolving, they will be mentioned briefly with references to the responsible company/standardisation body.

3.4.1 Security

Even though SNMP defines security provisions (in version 3), for certain reasons this is not always used [68]. One reason could be that security is self-contained and kept as independent as possible from other network services [7]. Something that would make it much easier for developers is when existing security standards and implementations can be reused, which is exactly that Web service-based security efforts attempt to accomplish.

WS-Security (version 1.0) [69, 70] and the Security Assertion Markup Language (SAML version 1.0) [71], both adopted by OASIS, are some of the important efforts currently underway for securing Web services. In essence, WS-Security defines how to construct secure SOAP messages. One core definition of WS-Security is about how to use XML-Signature [72] and XML-Encryption [73] with SOAP messaging. Another important definition is concerned with passing security tokens in SOAP messages. This type of security is thus focussed at encryption of the communicated messages.

SAML is a markup language that gives a specification for exchanging authorisation and authentication information. It includes bindings for WSDL/SOAP and could therefore be used in conjunction with Web services. It is very important for Web services security to have it integrate well with existing key and credential management infrastructure. A related standard is the XML Key Management Specification (XKMS) [74] which defines a protocol for distributing and registering public keys used in encrypting and decrypting messages.

Apart from Web services-related security measures, secure application protocols such as HTTPS [75] and S/MIME [76] could also be used. These can most certainly also be used for establishing secure connections to be used for SOAP message transport.

3.4.2 Transactions

Important initiatives that offer transactional functionalities are Web Services Choreography (WSCI version 1.0) [77], Business Process Execution Language for Web services (BPEL4WS version 1.0) [78] and the WS-Transaction Framework [79, 80, 81]. These initiatives are more or less overlapping, so it is just a matter of time to wait and see which kind of model will be implemented and used. A more extensive description and comparison of these initiatives can be found in an online article [82].

3.4.3 Reliability

In section 3.1 it was said that using TCP could make sure that SOAP messages are delivered correctly, once and in the right order. However, it could be possible that the SOAP messages need to travel over different networks (for example from internet onto the intranet) and thus several hops all using a different application protocol. Consider the case that SOAP is transported over HTTP on one hop and SMTP on another. Sometimes it is feasible to still support end-to-end reliable messaging, like in business operations such as the placement or cancellation of an order. These messages need to be reliably delivered and acknowledged [83]. To tackle this problem, WS-Reliability (version 1.0) [84] has been proposed by a number of companies and adopted by OASIS as WS Reliable Messaging [85] for further development. WS-reliability defines extra SOAP headers to ensure reliable messaging.

3.4.4 Summary

The list of Web service additions seems almost ever growing. The most important ones for network management have been discussed in this section, but many more exist, like: WS-Inspection, WS-Routing, WS-Referral, Web Services Flow Language (WSFL) and the WS-Notification family of specifications (WS-BaseNotification, WS-BrokeredNotification, WS-Topics).

Web services are relatively new and its base standards (WSDL and SOAP) are still in their very early versions and constantly evolving. This holds even more for the additional "standards", most of which have just reached a version 1.0 and only recently been handed over to a standardisation body like the W3C or OASIS.

For completeness, an overview of the main Web service standards as well as several additional standards is provided in figure 3.4. It is an attempt to place them in relation with SOAP and WSDL, as well as with each other.

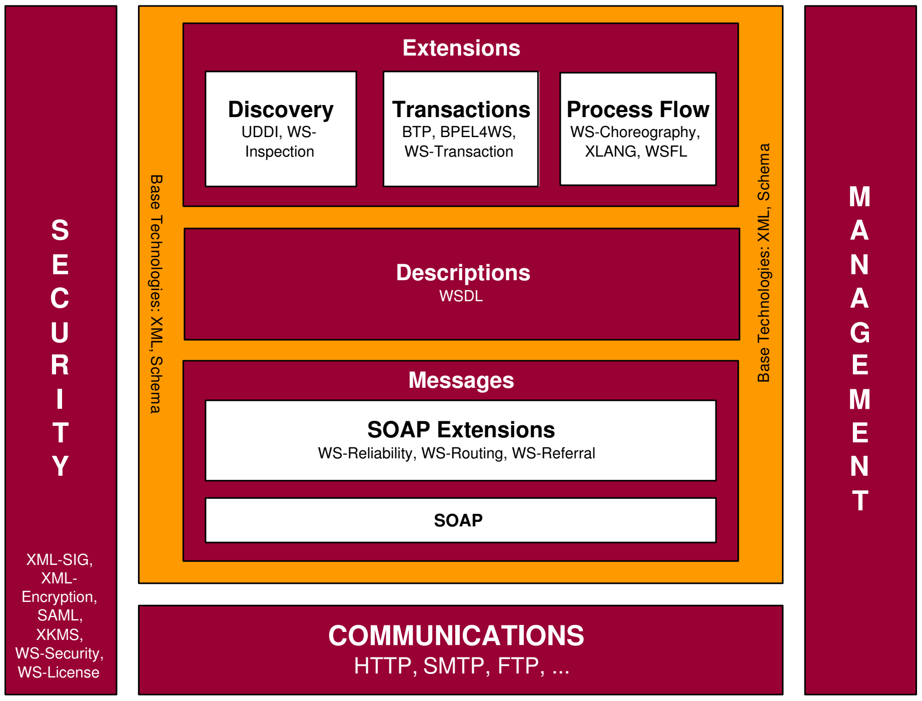

Extensions
Discovery
UDDI, WS-Inspection
Transactions
BTP, BPEL4WS, WS-Transaction
Process Flow
WS-Choreography, XLANG, WSFL
Descriptions
WSDL
Messages
SOAP Extensions
WS-Reliability, WS-Routing, WS-Referral
SOAP
Base Technologies: XML, Schema
Base Technologies: XML, Schema
SECURITY
XML-SIG, XML-Encryption, SAML, XKMS, WS-Security, WS-License
MANAGEMENT
COMMUNICATIONS
HTTP, SMTP, FTP, ...

Figure 3.4: Web service related standards

Chapter 4

Standardisation

The previous two chapters have presented the basic concepts of Web services and given an approach of how to apply Web services to network management respectively. But as with other management approaches, standardisation is a very important issue for the acceptance and usability of a particular approach.

This chapter will focus on the important parts of Web services that can be used for standardisation. As the previous chapter 3 has shown, there are many standards or other proposals related to Web services. Most of these focus on certain aspects of the Web services architecture and thus specify SOAP or WSDL extensions. This thesis regards network management as an application that can make use of the Web services architecture, hence standardisation for network management should also be based on the already existing Web service standards.

Therefore section 4.1 will discuss the modular capabilities of WSDL and explain why only a part of a WSDL definition can and should be standardised for network management. This part of a WSDL document contains operation and message definitions, both of which can have forms that vary significantly depending on the envisioned users and applications. This thesis considers a solution space with regard to standardisation of operations and messages in section 4.2. This will also include a discussion on the merits of extremes in the solution space. Finally this chapter concludes with an overview of possible modelling approaches for a management information model in section 4.3. This is accompanied by an explanation on the difference between data and information models.

4.1 WSDL modularisation

WSDL provides a mechanism to describe a Web service in a modular manner. This means that a WSDL document can be split up in parts and each part can be stored in a separate document, even at separate locations. For example, messages and interfaces could be defined in a single document, enabling another WSDL document to omit messages and interfaces by importing them instead. This enhances the reusability of the first document in such a way, that it can also be used for the definition of messages and interfaces of a WSDL document with a different service and/or binding component.

```
<definitions>
  <import location="http://example.com/wsdl/foo_interface.wsdl"/>

  <binding>...</binding>

  <service>...</service>
</definitions>
```

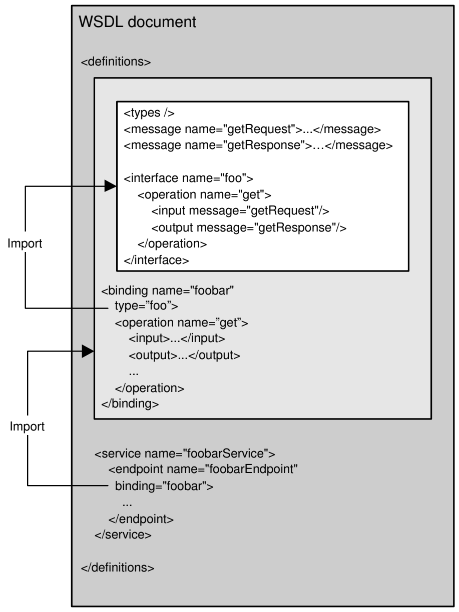
Listing 4.1: Import of interface WSDL

This functionality is achieved by the elements `<import>` and `<include>`. Both elements provide the same functionality of separating different components of a WSDL description, but `<include>` does this for components from the same target namespace, whereas `<import>` is used for different target namespaces [58]. Listing 4.1 gives an idea of how interfaces are imported from a separate WSDL document, having only the `binding` and `service` elements defined in the main WSDL document.

The UDDI Technical Committee (see section 2.2.1) recommends a division of WSDL documents into two separate WSDL definitions. One is the "*service interface definition*" part, which should contain the `<types>` (if any), `<message>`, `<interface>` and `<binding>` elements. The other WSDL definition is the "*service implementation definition*" part, which should contain the `<service>` element. Like the names suggest, it is an attempt to split up a WSDL definition in an interface part and an implementation part.

The above recommendation is an attempt to provide a best practice in modularising WSDL documents. However, it can be argued that bindings are better defined separate from the service interface definition. In principle, a binding bounds an interface to a certain message protocol (SOAP). But for standardisation it is more interesting to focus on the abstract definition, regardless of any protocol. On the other hand, bindings could possibly also be standardised separately, thereby making operations available through a default protocol and defining a standard encoding of the message parts. But it should not be part of a standardised abstract interface definition. Figure 4.1 shows how a WSDL document is built up, when a modular approach is used. This shows how a WSDL document can be separated into an abstract part containing the messages and interfaces (the **what** part), and two concrete parts: a binding (the **how** part) and a service (the **where** part).

For standardisation, the abstract part of a WSDL document is the most important, since the operations and messages are defined here. When standardising the abstract part of a WSDL definition, the need for a modular approach is again stressed by the fact that standards should be defined independent from each other and for different purposes, whilst running on the same management agent and offering a similar means of access. Much like SNMP, where for example the IF-MIB [86] and Host-resources MIB [87] are also defined by different persons, each standardising a disjoint set of management information, while all information from both MIBs can be accessed in a similar manner.



```
<definitions>
  <types />
  <message name="getRequest">...</message>
  <message name="getResponse">...</message>

  <interface name="foo">
    <operation name="get">
      <input message="getRequest"/>
      <output message="getResponse"/>
    </operation>
  </interface>

  <binding name="foobar"
    type="foo">
    <operation name="get">
      <input>...</input>
      <output>...</output>
      ...
    </operation>
  </binding>

  <service name="foobarService">
    <endpoint name="foobarEndpoint"
     binding="foobar">
      ...
    </endpoint>
  </service>

</definitions>
```

Figure 4.1: WSDL import mechanism

4.2 Management operations

The modularity of WSDL documents show how it is possible to define (and standardise) operations, messages and types irrespective of binding and service. The question remains what form operations, messages and types should take in order to provide feasible functionality. This section will provide an overview of the solution space.

4.2.1 Operation definition extremes

Now that is made clear how messages can be exchanged and what the corresponding interaction patterns are, it is time to have a closer look at the operations where these messages take part in. Messages and message exchange patterns are merely a means of structuring the parameters that an operation expects, their order and the possible fault messages. But it does not specify the functionality of an operation or what the result is after calling the operation.

Just as with SNMP, that uses a few generic operations, there needs to be agreement on which operations are to be supported for Web services. Of course, a very simple way is to translate SNMP operations directly to corresponding Web service operations, but Web services can provide more flexibility without necessarily increasing the complexity. Two extreme approaches are distinguished in [7]. One approach has basic operations on WSDL level, such as *get* and *set*, with parameters passed as opaque types. This means that parameters are not defined at WSDL level, although it is possible to specify them on a higher-level XML schema. Another approach is to define separate operations for each managed object, such as *getIfInOctets* or *changeIfoperationalStatus* that both provide management functionality for a part of a network interface. These operations only expect one parameter which is the index of the interface, to distinguish it from other interfaces in the same system.

This thesis states that in theory there are four different extreme approaches for the definition of management operations. As the example above already mentions, there can be a difference in the granularity of operations: coarse grained such as *get* and fine grained such as *getIfInOctets*. But for each form of granularity the parameters of operations can be either defined at WSDL level, or be kept opaque and possibly defined in a higher-level (XML) schema. This will be referred to as operations that have either transparent or non-transparent parameters at WSDL level. These extreme forms are summarised in figure 4.2.

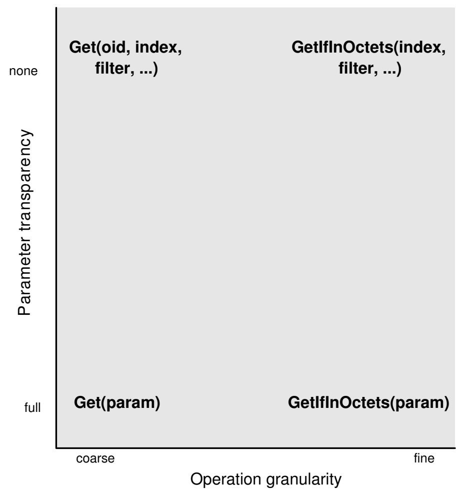


Figure 4.2: Operation extremes

4.2.2 Parameter transparency

The messages that are defined in a WSDL document and referred to from the operation definition can consist of several parts, each defined by a `<part>` element. The parts are used to actually comprise the parameters that an operation expects. However each parameter does not necessarily need to be directly mapped to a message part. There are several ways to do this.

The extreme forms have already been mentioned: parameters can be defined at WSDL level or be completely transparent from it. An example of non-transparent parameters where each parameter is also mapped at a single message part is given in listing 4.2. In this case there is only one input parameter of the *getIfTable* operation, but quite a number of output parameters.

On the other hand, parameters can also be combined and/or serialised in such a way, that the parameters are not described at WSDL level anymore. Merely their serialisation is described in a message part. This is called parameter transparency. In that case, serialising should be done upon composing a message and de-serialisation upon receiving it. This means that besides awareness of the operation parameters, a management application (and agent) should also offer (de-)serialisation capabilities. Listing 4.3 shows what the messages of

```
<message name="getIfTableRequest">
  <part name="community" type="xsd:string"/>
</message>

<message name="getIfTableResponse">
  <part name="ifIndex" type="xsd:unsignedInt" />
  <part name="ifDescr" type="xsd:string" />
  <part name="ifType" type="xsd:unsignedInt" />
  <part name="ifMtu" type="xsd:unsignedInt" />
  <part name="ifSpeed" type="xsd:unsignedInt" />
  <part name="ifPhysAddress" type="xsd:string" />
  <part name="ifAdminStatus" type="xsd:unsignedInt" />
  <part name="ifOperStatus" type="xsd:unsignedInt" />
  <part name="ifLastChange" type="xsd:unsignedInt" />
  <part name="ifInOctets" type="xsd:unsignedInt" />
  <part name="ifInUcastPkts" type="xsd:unsignedInt" />
  <part name="ifInDiscards" type="xsd:unsignedInt" />
  <part name="ifInErrors" type="xsd:unsignedInt" />
  <part name="ifInUnknownProtos" type="xsd:unsignedInt" />
  <part name="ifOutOctets" type="xsd:unsignedInt" />
  <part name="ifOutUcastPkts" type="xsd:unsignedInt" />
  <part name="ifOutErrors" type="xsd:unsignedInt" />
</message>

<interface>
  <operation name="getIfTable" pattern="http://www.w3.org/2004/03/wsdl/in-out">
    <input message="getIfTableRequest"/>
    <output message="getIfTableResponse"/>
  </operation>
</interface>
```

Listing 4.2: Multiple message parts with simple types

```
<message name="getIfTableRequest">
  <part name="requestPart" type="xsd:string"/>
</message>

<message name="getIfTableResponse">
  <part name="responsePart" type="xsd:string"/>
</message>
```

Listing 4.3: Single message parts with opaque types

the *getIfTable* operation would look like when operation parameters are made transparent at WSDL level.

An advantage of transparency is that management information is abstracted from protocol level, so the structure of information can change without having to modify the operation messages. Suppose a Web service supports an operation with full transparent parameters, such as in the bottom half of the graph of figure 4.2, then all parameters are serialised into one message part (called *param* in the example). In case the parameters are serialised in an XML structure, it can be contained in a message where the part has (XML-)string type. On both the manager and agent side, a generic XML parser can then be used to extract the parameters from the message.

Parameter transparency is not the only way to abstract management information from protocol level. Note that Web services are much more flexible with regard to data-types. It is possible at WSDL-level to define complex types, that also comprise all parameters for an operation. But since they are not defined in a message definition but as a type, the structure of the type can still change without having to modify the message structure. Using the modularity of WSDL

```
<types>
  <complexType name="ifEntry">
    <sequence>
      <element name="ifIndex" type="xsd:unsignedInt"/>
      <element name="ifDescr" type="xsd:string"/>
      <element name="ifType" type="xsd:unsignedInt"/>
      <element name="ifMtu" type="xsd:unsignedInt"/>
      <element name="ifSpeed" type="xsd:unsignedInt"/>
      <element name="ifPhysAddress" type="xsd:string"/>
      <element name="ifAdminStatus" type="xsd:unsignedInt"/>
      <element name="ifOperStatus" type="xsd:unsignedInt"/>
      <element name="ifLastChange" type="xsd:unsignedInt"/>
      <element name="ifInOctets" type="xsd:unsignedInt"/>
      <element name="ifInUcastPkts" type="xsd:unsignedInt"/>
      <element name="ifInDiscards" type="xsd:unsignedInt"/>
      <element name="ifInErrors" type="xsd:unsignedInt"/>
      <element name="ifInUnknownProtos" type="xsd:unsignedInt"/>
      <element name="ifOutOctets" type="xsd:unsignedInt"/>
      <element name="ifOutUcastPkts" type="xsd:unsignedInt"/>
      <element name="ifOutErrors" type="xsd:unsignedInt"/>
    </sequence>
  </complexType>
</types>

<message name="getIfTableRequest">
  <part name="requestPart" type="xsd:string"/>
</message>

<message name="getIfTableResponse">
  <part name="responsePart" type="xsd:ifEntry"/>
</message>
```

Listing 4.4: Single message parts with complex types

documents, these types can even be defined in a different WSDL document or other XML schema definition and imported when needed.

Listing 4.4 shows how operation parameters are comprised in a single message part, but still known at WSDL-level. Note that this approach does resemble complete transparency with an XML structure defined at application level, just the main difference is the explicit link between message part and part type. In both cases there is a need to define a higher-level XML schema. Examples of XML schemas for SNMP management information can be found in [10, 88].

On the service requester side using a higher-level XML schema means that there should be functionality to firstly create such an XML data structure before the Web service can be called. Also it should have provisions to handle incoming messages with complex XML data structures. This entails that it can only be used in either more specific network management applications or by more experienced users/developers. In other words, parameter transparency offers a very flexible and expressive use of operations, but this is only useful for professional users who need this kind of flexibility. For a PC user in his home environment who wants to include some management information in his spreadsheet, this will probably be too complicated. In that case, a simple operation is required where a user does not need to create complicated parameter structures in order to compose the messages in a correct form.

Thus only if expressiveness is wanted and the use of (XML) parsers is accepted, it is interesting to have operations with transparent parameters. Non-transparent parameters make operations easy to understand for users and easy to develop for developers.

For completeness it should be mentioned that it is also possible to have

```
<message name="getIfTableResponse">
  <part name="sizeTable" type="xsd:int"/>
  <part name="responsePart" type="xsd:ifEntry"/>
</message>
```

Listing 4.5: Multiple message parts with simple and complex types

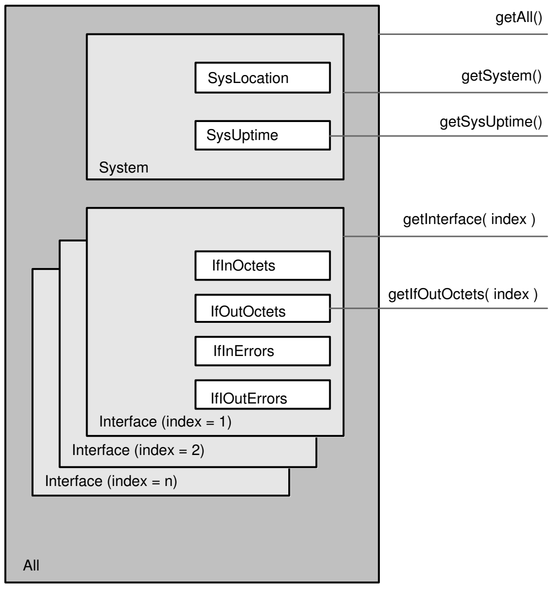


Figure 4.3: Containment diagram

messages with combinations of the above mentioned approaches (they are meant to denote the extreme forms). As listing 4.5 shows, a message can have a part with a simple type and a part with complex type at the same time. It can even have a part with transparent and a part with non-transparent parameters, however the usability of such a message structure remains questionable.

4.2.3 Operation granularity

The other degree of freedom is operation granularity: the level of variation between very coarse and very fine operations. In order to illustrate this, we will assume to have a managed system of which system information and network interface information can be requested. The variables for system information are rather straightforward, namely its location and uptime: *SysLocation* and *SysUptime*. The network interface information is a bit more complex, since a system can have more than one interface. Therefore the same variables can be retrieved for each single network interface: *IfInOctets*, *IfOutOctets*, *IfInErrors* and *IfOutErrors*. Figure 4.3 shows a containment diagram, which depicts these several types of information we can retrieve from a system.

In order to retrieve this information from the system, we can define operations that request the managed system for this information. If we consider using very fine operations we would get operations such as *getSysUptime* or

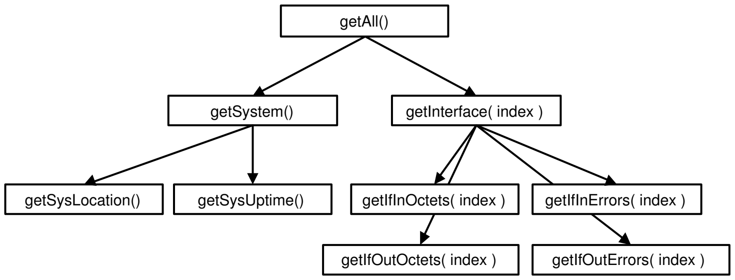


Figure 4.4: Containment tree

getIfOutOctets as is also shown in figure 4.3. So a fine granularity of operations means that for each variable a single operation is defined. Operations for network interface information need to have a parameter supplied to identify the interface.

Suppose one wants to request all information from one network interface. This would result in calling an operation for each single variable. Therefore, a bit coarser operations can also be defined, such as *getSystem*, *getInterface(index)* or perhaps even all information contained in the managed system. In that case, there is not only a single operation for each variable, but also for each container where *All* is the container that contains 'everything'.

An advantage of this approach is that if the naming of the operations precisely defines the functionality, it is very clear to a user which operation to call to retrieve the information he wants. Generally speaking, the parameters passed to an operation, be it transparent or not, can be simpler since selecting an object is already done by choosing the corresponding operation. In case of more than one instance of an object (such as the network interface example), an instance identifier (index) has to be provided.

Suppose someone wants to select different types of variables, such as all *System* variables and the *IfInErrors* of an interface with $index = 2$, then one is forced to call two separate operations. If we consider the containment hierarchy as a tree of fine operations (figure 4.4), then we can state that one fine operation does not allow selection in separate branches of the tree, e.g. one operation can not retrieve both *System* and *IfInErrors*. Only the operation corresponding to the node where these branches meet (*getAll*) would make it possible to retrieve this information. However, *getAll* does not only retrieve *System* and *IfInErrors*, but much more information that in this case would be redundant.

Suppose filtering the result would be possible on the agent side. This makes it possible to get all information that satisfies some criteria, or get all information with some exceptions or up until a certain depth of the tree. We will use the term filtering for any of these kinds of criteria. Theoretically filtering would make it possible to retrieve any single variable or container only using *getAll* together with a filter. This leads to the concept of a very generic operation, for instance *get*. When provided with a container-name or variable-name, a possible index and perhaps a (simpler) filter, *get* can be used to retrieve any kind of information on any level in the containment tree. In that case, *get* is an example of an extreme coarse operation, having a very generic name and used for more than a single task.

This behaviour would make *get* a very expressive operation, because with one single operation one can get any type of information from the managed system. It does make the parameters that should be passed to the operation more complex, whether they are transparent or not. It also poses a more complex naming problem. With fine operations, the network manager only needs to know which index to provide when it requests information from an object that can have more than one instance. On the other side, with coarse operations a network manager needs to know how to address any objects or instances on the agent side.

In an online MSDN article [89] there is a short discussion on granularity of interfaces of distributed systems in general. It states that a fine-grained interface is very likely to impede application performance, because it generally requires many method calls to achieve certain functionality, since each method encapsulates just a very small piece of functionality. It further states that therefore remote objects should define a coarse-grained interface that exposes only a small set of methods. Each method should typically offer high-level functionality, like Place Order or Update Customer (compare with *get* or *set* operations) and all the data that a method needs should be passed as a parameter.

This view is also supported by the IONA [60] in a white paper on using MDA to develop Web services. It states that Web services should also provide coarse-grained operations that are compositions of more primitive functionality. It envisions that objects (in the object-oriented sense) defined on a service provider should not expose all their specific, fine-grained operations as a Web service, because they are not likely to provide the needed service to a service requester. It should rather provide operations that provide much more application logic, thereby most likely reducing network traffic since less interactions are needed compared to fine-grained operations, to provide a similar level of functionality.

4.2.4 Summary

We have distinguished four extreme forms of management operations, all of which have some advantages and disadvantages. Operation with non-transparent parameters are more likely to be used easily, since parameters are defined at WSDL level. When types are kept simple, it is very easy for a simple user in a home environment to include management information in for instance a spreadsheet or word processing document. The disadvantage of specifying management information at WSDL level is that in case the management information changes, the WSDL also needs to be modified and possibly also management applications.

This in contrast to transparent parameters, where management information is abstracted from protocol-level. This does pose the need for a higher-level (XML) schema for the definition of management information. The result is that even though this approach seems more flexible and expressive, it is more likely to be used by professional operators. It can be more complicated to create a higher level message structure in "simple", generic applications such as spreadsheets.

An advantage of having very coarse-grained operations is that the Web service definition can be kept rather simple, with regard to the number of available operations. The implementation of such an operation however, is likely to be more complicated than fine-grained operation, same as for the structure of parameters. Users of these operations also need to know less operations, although they are possibly more complex. Fine operations can be easily understood, since it does not require extensive knowledge on an underlying data model (no need to provide parameters referring to variables, except indices). This could prove to be useful in generic applications. However, it also makes way for an ever-growing number of operations. With regard to this discussion it is interesting to see general statements on distributed systems/Web services, claiming that coarse-grained operations are the best solution for invoking remote operations.

The choice for a certain granularity will be a trade-off between simplicity and expressiveness. However, with the extensibility of Web service interfaces it is possible to have, for instance, both a standardised interface with coarse-grained operations, as well as a (proprietary) extended interface with fine-grained operations.

4.3 Management information definition

4.3.1 Data models and information models

Management information in current standards is typically comprised in data models, such as SNMP MIBs and the DMTF CIM (see also section 1.5). The usefulness of standardised data models is ensured by keeping the objects that represent a particular resource the same at each managed system and by using a common scheme for representation of management data to support interoperability.

But a distinction can be made between data and information models. In RFC3444 [90] is explained how models can be described at different abstraction levels. An information model (IM) is defined on a higher abstraction level than a data model (DM). An IM can be considered to have easier to grasp concepts behind it, since it should hide all protocol and implementation details. A formal definition of an IM can be found in RFC 3198 [91]:

> *"An abstraction and representation of the entities in a managed environment, their properties, attributes and operations, and the way that they relate to each other. It is independent of any specific repository, software usage, protocol, or platform.".*

The same RFC gives the following definition for a DM:

> *"A mapping of the contents of an information model into a form that is specific to a particular type of data store or repository. A "data model" is basically the rendering of an information model according to a specific set of mechanisms for representing, organising, storing and handling data.".*

In other words, a DM is an "implementation" of an IM. The availability of a number of different implementation platforms entails that a single IM can result in several DMs. Suppose a general management IM exists, one can state that both the SNMP MIBs defined in SMI, and the DMTF CIM defined in Managed Object Format (MOF) (not to be confused with the MOF as is known from MDA: the Meta-Object Facility) are the DMs. This is depicted in figure 4.5.

However, to date merely the DMs of management information exist. These models generally contain lots of details and are therefore not always easily understood. The CIM has an accompanying set of non-normative UML class

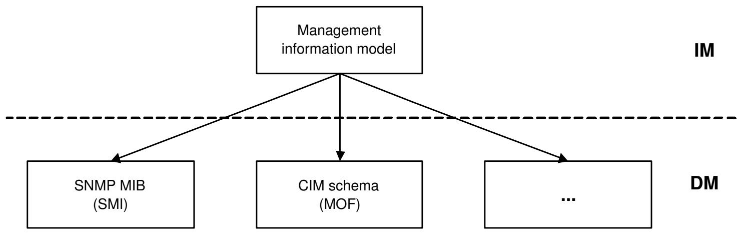


Figure 4.5: Management IM and DMs

diagrams based on the MOF definitions, but they do not contain all aspects since some of that is not possible to model in UML.

Based on this observation, as well as remembering the typical usage of MDA techniques, it can be of interest to define an abstraction of the existing management DMs, thereby creating a management IM (or a platform independent model, in MDA terminology). Theoretically one could define a transformation that could map this IM to MIBs or CIM schema definitions and thus creating a platform specific model. This management IM could be defined in a variety of languages, like UML class diagrams or Entity-Relationship (ER) diagrams. Of course, natural (English) language is also an option, however this is not useful for MDA and can hardly be used for (automatic) model transformation.

RFC 3444 mentions that UML has an advantage above other modelling techniques, especially because it is being widely adopted in the industry and taught in universities. Also, UML is standardised (by the OMG) and many tools for editing UML diagrams are now available. And even though MDA does not impose the use of UML, current MDA tools (like ArcStyler and Objecteering) are commonly based on UML modelling.

Furthermore RFC 3444 finds it advisable that in general object-oriented techniques should be used to describe an IM. Important advantages of object-oriented techniques are the notions of abstraction and encapsulation, as well as the possibility of object definitions to include operations. So even though ER diagrams could be very useful to describe management information and relationships in a more abstract level, they do lack these object-oriented characteristics.

4.3.2 Management information models

As mentioned before, an IM can be defined in a variety of modelling techniques. But different modelling techniques impose different kinds of models, in which management information can be defined in different ways. This section makes a distinction between various types of models, namely data-oriented, task-oriented and object-oriented. These are based on [92], where a similar distinction is made between approaches for network management protocols. Although, instead of the terms data-oriented and task-oriented, it uses the terms variable-oriented and command-oriented respectively.

A data-oriented model focuses mainly on management information itself, where each piece of information is comprised in a variable (hence variable-oriented in [92]). Generally, such a model does not contain operations. For example, ER diagrams can be considered data-oriented by nature, since it focusses on the data modelling and the relationships between related groups of data (entities). It is not possible to model operations in this type of diagram. An example of a data-oriented DM is a MIB defined in SMI.

IMs can also be task-oriented. This kind of model defines tasks that typically have well-defined semantics. Examples of commands are: *reset*, *reboot* or *close all connections*. In other words, management functionality is divided in a number of tasks that can be performed on the managed system. Natural language (English) is very suitable for describing task-oriented models. An example of a DM that could be considered task-oriented is WSDL, which abstracts from underlying data structures by only defining operations.

Finally object-oriented models can be distinguished. They can be seen as a combination of variable-oriented and command-oriented models, since they define objects that can expose both attributes (variables) and operations. A manager then invokes operations on these objects and receives notifications with the result. UML diagrams are highly suitable for modelling an object-oriented management IM. CIM can be regarded as an example of an object-oriented management DM, even though they are probably closer to IMs than for instance the SMI MIB DMs [90].

The following two sections will focus on data-oriented ER diagrams and object-oriented UML class diagrams and discuss their suitability for modelling an IM. Task-oriented models will not be discussed here, because of the preassumption that they should be modelled in natural language. This is not very suitable for usage in an MDA tool, although it could be a topic for further research.

4.3.3 Data-oriented information model

Database analogy

Before explaining how ER diagrams can be used to define a data-oriented IM, firstly it is interesting to recognise the analogy of MIBs with databases. Management information defined in MIBs is data-oriented by nature. In [1] we can find the following description of a MIB: "*In essence a Management Information Base is a database structure in the form of a tree*". Such a description of a MIB makes an analogy with traditional Database Management Systems (DBMS) valid. In fact, the SNMP architecture and data definition can easily be compared with a so-called multi-database system (MDBS) architecture. In [93, p.87] a classification schema of distributed databases is given, with variations along three axes: the autonomy of local systems, their distribution and their heterogeneity. An MDBS is a homogenous collection of autonomous databases without distribution.

We consider the analogy of a local DBMS that is part of a distributed database with an SNMP agent that is part of a network management system. Suppose an SNMP agent is regarded as a DBMS containing management information of that particular device, then all agents in a certain network in principle have the same DBMS, each having identical functionality and interface. This is an example of homogeneity. Agents can be regarded as being autonomous, since each agent does not know the presence of other agents, nor the concept of cooperation with them. Finally, management information is not really distributed. Each agent has, in principle, the same database structure, but containing its own information. The architecture is not meant to be distributed and transparent to a manager anyway, since the location of information plays a vital role in network management.

A network manager in its turn can then be compared to some sort of global database manager that has control over each individual DBMS. In DBMSs it is also common to have a few generic operations, that can be used to query any database. The most commonly used query language for databases is the Structured Query Language (SQL) and even though it is standardised by both ANSI and ISO [94], many variations exist across implementations of different vendors. The SQL standard offers four basic operations that together form the SQL data-manipulation language (DML) [95, p.1]:

- `SELECT` - retrieves data from a database by providing a description of the desired result set
- `UPDATE` - modifies existing data in a database table, but does not remove it
- `INSERT INTO` - inserts a new row in a database table
- `DELETE` - removes rows from a database table

SQL offers much more functionality than will be discussed here, such as creation/deletion of databases and tables, indexing, definition of views, transactions, locking and access control. The focus here will be on the data definition and relations. SQL is a set-based programming language that allows for the manipulation of data stored in two-dimensional tables, also referred to as a relation. The name of a particular relation and the corresponding set of attributes is called a schema. Suppose a relation named *Interface* has the following schema:

```
Interface( Description, Speed, PhysicalAddress )
```

then *Interface* is the name of the relation and *Description, Speed and PhysicalAddress* are its attributes. The attributes depict the structure of the table, thus a valid row in this table would be:

```
( eth0, 100, 0:0:b4:a9:1:5a )
```

A row in a table is formally called a tuple and its attributes are called components of a tuple. The relational database model requires each component to be of some sort of atomic type, i.e. they can't be tables, sets, arrays or other structures.

Description	**Speed**	**PhysicalAddress**
eth0	100	0:0:b4:a9:1:5a
eth1	100	0:5:c6:c1:4d:6c
eth2	10	0:5:8d:8:7a:4b

Table 4.1: Interfaces relation.

The operations from the SQL DML are set- or tuple-based and are designed to retrieve, modify, insert or delete one or more tuples from a table. `SELECT` and `UPDATE` can also work on components of a tuple. For example, consider

Description	Speed	PhysicalAddress
eth0	100	0:0:b4:a9:1:5a
eth1	100	0:5:c6:c1:4d:6c
eth2	10	0:5:8d:8:7a:4b

Table 4.2: Query: `SELECT * FROM Interfaces`.

Description
eth0
eth1
eth2

Table 4.3: Query: `SELECT Description FROM Interfaces`.

the table of 4.1 then tables 4.2, 4.3 and 4.4 give the result sets of three simple `SELECT` queries. It shows a little how powerful SQL queries can be.

With SQL much more powerful queries are possible by joining relationships, creating unions or intersections of result sets, etc. This shows that SQL is a language that can be used and understood very easily, like the simple examples in this section show, but also be used in a very powerful way by creating very complex queries. SQL has proven itself to be a language understood and used by many people, varying from simple home users to very professional users, and yet it only offers very few operations to the user.

A feature of databases is also that they can contain triggers. A trigger is an action that can take place after a certain defined event has occurred. Usually this happens after a table has been accessed in a certain way. When an event occurs, some operation can be performed, which is defined in a database specific programming language. One can think once again of the analogy with network management and more specific: SNMP traps. A trap can be compared with a database trigger, albeit that they usually do not take place after data access, but after some error has occurred at the agent side.

Entity-Relationship diagram

Databases can be modelled in various ways. There is not a single definition language. Some use natural language, others a formal language or even graphical tools, but all focus on data relationships. A very common modelling technique for databases is the Entity-Relationship diagram. This diagram can be used for describing the tables in a database and the relationships between them. This kind of diagram abstracts from any database specific definitions, and thus a database model can be regarded as an IM.

Description	Speed	PhysicalAddress
eth2	10	0:5:8d:8:7a:4b

Table 4.4: Query: `SELECT * FROM Interfaces WHERE Speed=10`.

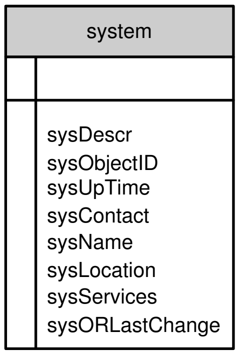


Figure 4.6: System information ER diagram

Recalling the analogy of DBMS's with network management, we can regard a MIB as database model for a particular kind of data. The difference is that in MIBs data is not only comprised in a table, but also as scalars that appear not to have any relationship with other scalars. However, MIBs are collections of related managed objects, i.e. there appears to be some sort of conceptual relationship after all. One way this can be explained, is by describing the system information defined in the SNMPv2-MIB. It consists of the following scalars: *sysDescr, sysObjectID, sysUpTime, sysContact, sysName, sysLocation, sysServices* and *sysORLastChange* as well as a table called *sysOrTable*.

Figure 4.6 could be a possible ER diagram to comprise this kind of information. It has the scalars with system information contained in a table called *system*. Of course it is clear that this is not a real table, since it may only contain one single row.

This can have a large influence on the naming of objects, or cells. MIBs (and thus SNMP) rely heavily on object identifiers and their ordering in the SNMP naming tree. But database-style models are very much focussed on data and relationships, resulting in a more expressive, but not necessarily more complicated (as the widespread usage of SQL shows) way of accessing data.

Another advantage of focussing more on relationships is that modelling redundant data can easily be avoided. For example, consider parts of the IF-MIB and the Host-Resources MIB. The first defines information on network interfaces and the latter on the software and hardware running on host computers connected to the internet directly used by human beings. The Host-Resources MIB therefore also contains a table with network interfaces available on the host. The only column in this table contains indexes which should correspond to the indexes in the network interface table from the IF-MIB. The way this relationship is modelled in the Host-Resources MIB definition [87] is by natural language. In an ER diagram, this can be explicitly modelled by using primary and foreign keys, as figure 4.7 shows. A primary key in a table should uniquely identify each table entry, whereas a foreign key points to a primary key in a different table.

For instance, the *hrDeviceTable* can contain devices that are network interfaces. Specific information for network interfaces is contained in the *hrNetworkTable* table. Each device has a unique index, also called primary key, namely *hrDeviceIndex*. This is used as a primary key in both the *hrDeviceTable* and

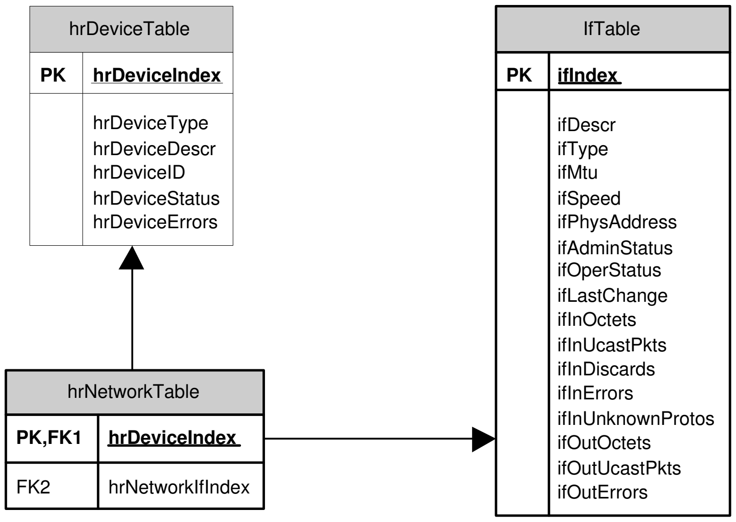


Figure 4.7: IfTable ER diagram

the *hrNetworkTable*. Moreover, the *hrDeviceIndex* should be the same in both tables, which is ensured by defining *hrDeviceIndex* as a foreign key of the *hr-NetworkTable* as well. Anytime an entry is added in the *hrNetworkTable*, the database should check if the index already exists in the *hrDeviceTable*. The Host-Resources MIB defines by natural language that each entry in the *hrNet-workTable* should also be contained in the *IfTable*. This is ensured by defining another foreign key that relates the *hrNetworkIfIndex* to the *IfIndex* of the *IfTable*.

In fact, modelling in such a way makes immediately clear that there is a redundant table, namely the *hrNetworkTable*. This table has a one-to-one relation with the *IfTable* and better design practice would be to have the *IfTable* contain a field called *hrDeviceIndex*, which functions as a foreign key to the *hrDeviceTable*.

4.3.4 Object-oriented information model

Modelling IMs can also be done using an object-oriented approach. This section will regard a managed object in the traditional object-oriented sense. This means that a managed object represents a "tangible" entity, that is part of a managed system. Examples of "tangible" entities are: CPU, network interface, hard disk, but also running software, TCP protocol, SNMP protocol, etc. Each object has an interface that abstracts from its internal structure by providing operations to other objects. Attributes of an object can not directly be retrieved, this needs to be done by accessor operations. For a more elaborate and detailed description of object-oriented design, the reader is referred to [96].

There has been an attempt to comprise SNMP management information in an IM, based on UML class diagrams [97]. In [98] a heuristic algorithm is presented to automatically translate MIB modules to UML class diagrams. However this algorithm has a number of limitations, because it depends on many "unwritten" rules for writing MIB modules, varying from the naming of managed objects to the introduction of new data types. The algorithm expects related objects to have a similar prefix in their names, but this is not mandatory in SMI. Also it is said that good MIB authors should define their own data types, which the algorithm can then use to recognise references between tables. This algorithm is an integrated part of the *smidump* program which is part of the *libsmi* SMI compiler package [99].

Chapter 5 explains in more detail how object-oriented IMs can be used to derive Web services (or rather a framework that needs more implementation) by making use of an MDA tool.

4.3.5 Summary

A distinction between a data-oriented, a task-oriented and an object oriented IM for the definition of management information. A data-oriented IM can typically be modelled as an ER diagram, a task-oriented IM in natural language and on object-oriented IM in UML. Since both data-oriented and object-oriented IMs can be modelled in a rather formal modelling language, it is interesting to investigate these for use with MDA tools.

Since the concepts are rather similar, ER diagrams can be relatively easily derived from SNMP MIBs, but this is only based on the examples given. This is an issue for further research.

An attempt has been made to reverse engineer MIBs to object-oriented UML class diagrams, but still a lot needs to be done by hand. An advantage of this approach is that current MDA tools (like Objecteering and ArcStyler) are commonly UML based. UML is much more elaborate than ER diagrams, already because it is able to model behaviour.

Chapter 5

Case study: host-resources

In this chapter the theory and ideas from the previous chapters shall be applied to create a Web service using an MDA tool. The tool of choice is ArcStyler (version 4.0.108) [100], since it provides good documentation in order to quickly and easily get to know the tool and make use of it.

The Web service that will be created will be based on the management information stored in the Host-resources MIB. This can be regarded as a MIB with easy to grasp concepts behind it, plus it contains both single variables and conceptual tables. Firstly the purpose of the Host-resources MIB shall be explained in section 5.1. After this, a Web service will be created based on a data-oriented approach (explained in terms of an EM diagram) in section 5.2. This will be a Web service that resembles SNMPv2 functionality, to explain how SNMP resembles Web services and to explain how coarse-grained operations will have its influence on the WSDL definition. Finally, section 5.3 presents how an object-oriented information model could be generated from the MIB definition and how this information can be accessed through many very fine-grained operations.

5.1 Host-Resources MIB

Before creating a Web service based on the Host-Resources MIB, the purpose of this MIB module shall firstly be explained. The Host-Resources MIB specifies which information is managed on a host. A host is defined as [87]:

> *"The term "host" is construed to mean any computer that communicates with other similar computers attached to the internet and that is directly used by one or more human beings."*.

Generally, a host is a computer connected to the internet and used by one or more persons. It can be argued how a general definition of a host can lead to a formal specification, therefore some descriptions shall be given firstly.

A general idea of a host is a computer system consisting of a CPU, (logical) disk and a network interface (since the definition requires it to be connected to the internet). Many systems will also have devices such as printers, sound cards, cd-rom drives and keyboards attached. A host also has one or more operating systems installed and software running on it. It is clear that this list is not exhaustive, since new devices and software are developed all the time. Furthermore, a host can change its configuration over time. Despite these facts, there is a core set of items that are consistent across all systems, even if they are given different names. The components in this core set can be classified in two categories:

- a hardware device
- a software package (such as a program or a collection of programs)

As mentioned before, the list of hardware devices is open-ended. Every distinct piece of hardware on a host is a device. At least 3 characteristics are mentioned by [101] which are common to all devices, regardless of their function:

- an indication of the manufacturer and product model
- a current status
- the number of errors that the device has reported

Of course more specific information can be managed for a certain device, but this highly depends on the type of device. A short and simple idea of this more specific information is given in the following list:

- **processors**: processor load, firmware version
- **printers**: status (such as: printing, idle or error has occurred), detected error, paper left
- **disks**: media access (RO or RW), type (such as: floppy, HD, cd-rom), capacity, partitions, file-systems, the partitions that comprise a given file system

There are 3 general categories of software packages [101]:

- **operating system**
- **device driver**
- **user application**

This clear distinction between software categories has been made for management purposes. For any program it is useful to know where it is installed, if it is running and what its status is (for instance waiting for an event or resource). It could also be useful to know how many system resources a program is consuming.

5.2 Data-oriented approach

Now that the purpose of the Host-Resources MIB is clear, a Web service will be constructed following the data-oriented approach. This part of the case study will be based on the operations defined in the SNMPv2 protocol. This is to show how SNMP and Web service could offer very similar functionality, but also to give an idea of a situation with coarse-grained operations.

5.2.1 Information model

In section 4.3 a data-oriented approach for the definition of an information model of management information was discussed. An analogy with databases was recognised and it was shown that it was relatively easy to define an ER diagram with management information.

However, for the sake of simplicity a new naming scheme for objects in an ER diagram will not be given here. Instead, the naming as defined in the Host-resources MIB will be used, to simplify the explanation of coarse-grained operations based on SNMP. In other words, this example will be using SNMP's data model instead of an information model. Another reason is that ArcStyler is based on the use of UML diagrams and therefore it can not use ER diagrams for automatic model transformation. This could be an interesting topic to investigate in the future though. But most probably model transformation then needs to be done manually.

It is nevertheless worth mentioning how the Host-resources MIB could be mapped to an ER diagram and thus this is included in appendix B.

5.2.2 Protocol

Management operations

Section 2.1.4 explains the operations that are used in SNMPv2 and depicts the corresponding message structures. These operations are: Get, Get-next, Get-Bulk, Set, Inform, SNMPv2-Trap. This section will give a simple translation of these operations to WSDL definitions.

These operations together with their corresponding sequence diagrams, lead to the design of WSDL operations as shown in listing 5.1.

The *PDU type* and the *request-id* fields are omitted, since they have no meaning on WSDL level. The "PDU type" of a WSDL message is in fact comprised in the operation name. And the request-id is not useful since a mechanism to differentiate which response belongs to which request is already available.

Message structure

Section 2.1.4 also explained the PDU formats that are used for a certain operation. These PDU formats can directly be related to WSDL message descriptions. This example does not attempt to provide the most accurate transformation of the SNMP PDUs to WSDL messages possible, but it should give a clear idea of how SNMP functionality can be achieved in WSDL.

It makes use of several types that are defined in an XML Schema-based structure. The complete type definition can be found in appendix E. This example makes use of non-transparent parameters, but with several message parts that have a type defined in an external schema. Of course, these types could just as well be defined in the WSDL definition, but it is kept separate for readability.

Recall from SNMP that the *variable-binding* part of a PDU, is a list of name-value parts. However, the length of the list (i.e. the number of pairs) is not known at definition time. Therefore it needs to be defined recursively. In SMI this is done by defining a *VarBindList* type, such as in listing 5.3 and in WSDL

```
<operation name="get">
  <input message="tns:requestMessage"/>
  <output message="tns:responseMessage"/>
  <fault message="tns:errorMessage" name="error-status"/>
</operation>

<operation name="get-next">
  <input message="tns:requestMessage"/>
  <output message="tns:responseMessage"/>
  <fault message="tns:errorMessage" name="error-status"/>
</operation>

<operation name="set">
  <input message="tns:requestMessage"/>
  <output message="tns:responseMessage"/>
  <fault message="tns:errorMessage" name="error-status"/>
</operation>

<operation name="get-bulk" parameterOrder="non-repeaters max-repetitions variable-
      binding">
  <input message="tns:get-bulkRequest"/>
  <output message="tns:responseMessage"/>
  <fault message="tns:errorMessage" name="error-status"/>
</operation>

<operation name="trap">
  <output message="tns:trapMessage"/>
</operation>

<operation name="inform">
  <input message="tns:trapMessage"/>
  <output message="tns:responseMessage"/>
  <fault message="tns:errorMessage" name="error-status"/>
</operation>
```

Listing 5.1: SNMPv2-style operations

```
<message name="requestMessage">
  <part name="variable-binding" type="xsd1:VarBindList"/>
</message>

<message name="responseMessage">
  <part name="variable-binding" type="xsd1:VarBindList"/>
</message>

<message name="get-bulkRequest">
  <part name="non-repeaters" type="xsd:int"/>
  <part name="max-repetitions" type="xsd:int"/>
  <part name="variable-binding" type="xsd1:VarBindList"/>
</message>

<message name="trapMessage">
  <part name="sysUpTime" type="xsd1:ObjectName"/>
  <part name="snmpTrapOID" type="xsd1:ObjectName"/>
  <part name="variable-binding" type="xsd1:VarBindList"/>
</message>

<message name="errorMessage">
  <part name="error-status" type="xsd1:error-status"/>
</message>
```

Listing 5.2: SNMPv2-style messages

```
−− variable binding

VarBind ::= SEQUENCE {
        name ObjectName,

        CHOICE {
            value ObjectSyntax,
            unSpecified NULL, −− in retrieval requests

                                        −− exceptions in responses
            noSuchObject [0] IMPLICIT NULL,
            noSuchInstance [1] IMPLICIT NULL,
            endOfMibView [2] IMPLICIT NULL
        }
    }

−− variable−binding list

VarBindList ::= SEQUENCE (SIZE (0..max−bindings)) OF VarBind
```

Listing 5.3: VarBindList type definition (SMI)

this should be done in a very similar way: defining a *VarBindList* type. The XML Schema definition for this type is listed in 5.4. The similarities between these two definitions are rather clear: in SMI the *VarBindList* type is a sequence of *Varbind* types with minimum number of occurrences is 0 and the maximum number of occurrences is *max-bindings*. In XML Schema this is the same, only with the maximum number of *Varbind* occurrences *unbounded*. The complete XML Schema for SNMP-based types can be found in appendix E.

5.2.3 Summary

SNMP can be modelled as a Web service as well. In that case it is possible to use SNMP-like operations and addressing, while at the same time one can make use of the provisions that Web services (will) offer, such as security and transactions.

The abstract interface definition as discussed in this section is not meant to be an accurate specification of SNMP functionality in WSDL. Especially with regard to data types, there is a lot to improve since mostly generic XML Schema string types are used. The complete WSDL abstract interface definition for a simple SNMP-like Web service is listed in appendix C. For completeness, a binding definition is also provided for this Web service in appendix D. This is once again an example of WSDL modularity: the binding definition imports the abstract interface definition. The abstract interface definition in its turn uses the XML Schema import mechanism to import special data types that need to be used for this particular Web service.

5.3 Object-oriented approach

This section will describe how a network management Web service can be developed using an object-oriented approach. Where the data-oriented approach focussed on coarse-grained (SNMP-based) operations to access them, this approach will focus on deriving an object-oriented information model (UML class diagram) from the MIB definition and defining fine-grained operations. Consid-

```
<xsd:complexType name="VarBindList">
    <xsd:sequence>
        <xsd:element maxOccurs="unbounded" minOccurs="0" name="varbind" type="
            xsd1:VarBind"/>
    </xsd:sequence>
</xsd:complexType>

<xsd:complexType name="VarBind">
    <xsd:sequence>
        <xsd:element maxOccurs="1" minOccurs="1" name="name" type="xsd1:ObjectName"/
            >
        <xsd:choice>
            <xsd:element name="value" type="xsd:string"/>
            <xsd:element name="unspecified" type="xsd:string"/>
            <xsd:element name="noSuchObject" type="xsd:string"/>
            <xsd:element name="noSuchInstance" type="xsd:string"/>
            <xsd:element name="endOfMibView" type="xsd:string"/>
        </xsd:choice>
    </xsd:sequence>
</xsd:complexType>

<xsd:simpleType name="ObjectName">
    <xsd:restriction base="xsd:string"/>
</xsd:simpleType>
```

Listing 5.4: VarBindList type definition (XML Schema)

ering that management information as defined in the Host-resources MIB shall be modelled, it is logical to use the *smidump* program which is described in section 4.3.4 as it provides an algorithm for reverse engineering MIB modules to UML diagrams.

5.3.1 Information model

The first step is to let *smidump* convert the Host-resources MIB module definition to a UML class diagram. The generated diagram is stored in the internal format of DIA, which is an open source UML editor [102]. This editor can then be used to display the result, which is included in appendix F.

Because of the limitations of *smidump* the generated model is not completely correct. Certain relationships have been generated that do not exist, most probably because of some confusion with indexes. Also a *hrStorage* class has been generated with only one attribute *hrMemorySize* that could easily be combined with the *hrSystem* class. The *hrMemorySize* variable contains "the amount of physical read-write main memory, typically RAM, contained by the host" and can also be seen as an attribute of the system. This simplifies the model by reducing it with one class.

Summarising, some modifications on the generated model had to be made manually, resulting in a revised UML class diagram. A simplified diagram is depicted in figure 5.1 that shows a few less relations between objects than the generated diagram. The full diagram (including attributes) is presented in appendix G.

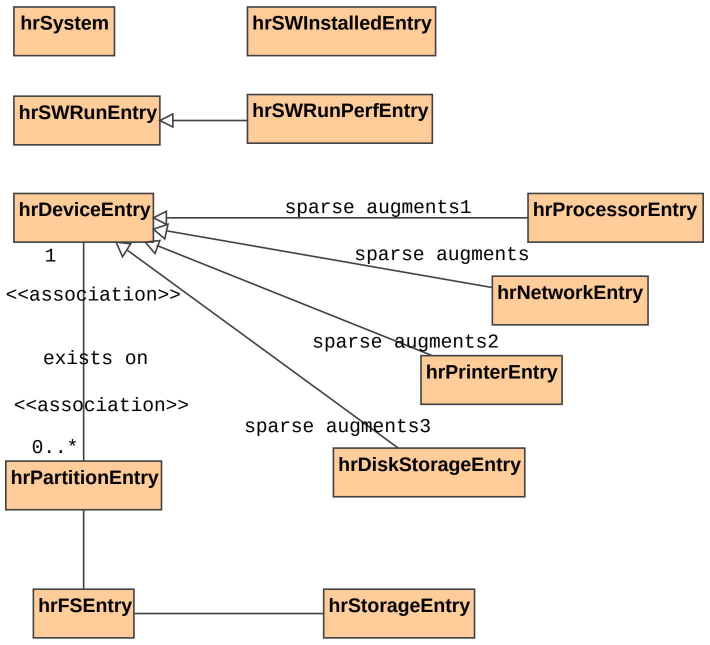


Figure 5.1: Simplified Host-resources UML class diagram

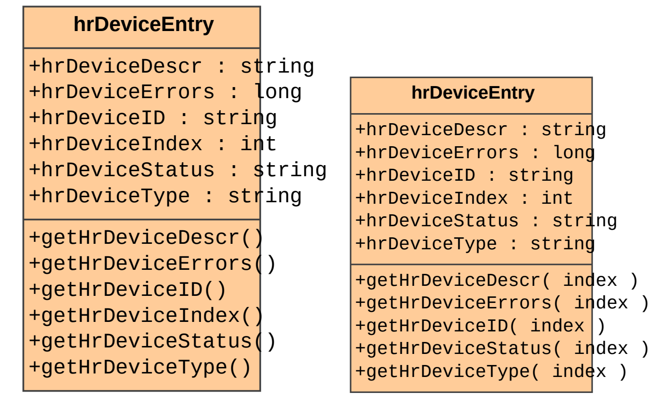
5.3.2 Protocol

Management operations

The revised UML class diagram forms the basis for creating the management Web service. This shall be done with ArcStyler that can use the UML class diagram to generate the Web service. ArcStyler contains a built-in UML editor, thus the DIA UML class diagram is easily inserted in ArcStyler. In fact, figure 5.1 is the UML diagram drawn in ArcStyler.

The next step is the modelling of the Web service operations, which should show what a situation with very fine-grained operations looks like. Similar to the approach that has been adopted in [32], where operations are defined at protocol- and object-level, this example will have operations that can be regarded to be at object-level. For each attribute of each class an accessor will be created. Each attribute will have at least a read operation, though sometimes it may also have a write operation. The choice for having read-only or read-write attributes are made depending on the way this is defined in the Host-resources MIB. This form of accessibility is unfortunately not depicted in the generated class diagram.

Unlike MIBs, where each value has a certain fixed number assigned to it, objects in a UML class diagram pose a naming problem: some objects can have only one instance (like *hrSystem*) and some can have more than one (*hrDeviceTable*). This distinction is typically made for objects that are derived from table entries (each entry can represent an object instance) and for objects that are derived from (combinations of) related variables not part of a table. An object that can have only one instance is called singular. Given the fact that an



(a) Non-indexed operations (b) Indexed operations

Figure 5.2: *hrDeviceEntry* class definition.

object is called remotely, the Web service should provide a way of referring to a particular instance of that object, followed by invoking an operation on that instance.

In principle Web services provide ways of accessing operations from objects, but not from particular instances. In other words, by exposing only operations from objects, a Web service can normally not differentiate between instances. Therefore an instance reference should be provided when invoking a Web service operation, so the Web service can invoke that same operation on the referenced instance. Recall from MIBs that table entries are all identified by a certain index, thus objects that can have multiple instances, will have this index as an attribute. This index will thus be different for each instance and can therefore be used to differentiate between them. This index should be provided when calling an operation through a Web service.

For example, the *hrDeviceEntry* object (figure 5.2(a)) can have multiple instances. Each attribute is read-only according to the MIB definition, therefore only get-operations are defined for each attribute. For any normal object this would suffice, but since all operations are exposed as Web service operations, they should expect the instance index as parameter. This results in the operations definitions from figure 5.2(b).

Note that the operation *getDeviceIndex()* is omitted in figure 5.2(b), since it would make no sense. The index needs to be known before calling any operation which in itself could be a problem. How does a user know the index on forehand? One way to tackle this problem is given by WBEM, which defines operations that are not related to the defined objects. Although WBEM (see section 1.5.3) is not based on Web services, this idea can be applied to Web services as well. WBEM includes operation such as *GetClass, GetInstance, DeleteClass, DeleteInstance, CreateClass, CreateInstance, ModifyClass, ModifyInstance, EnumerateClasses*, etc. In principle, these operations enable a user to choose certain objects, request references to all its instances and then invoke an operation on a particular instance. Summarising, in order for a Web service with very fine-grained operations (like accessors for each attribute) to

```
<portType name="com.io_software.catools.cmod.cmod.foundationJMIImpl.
      CAClassImpl@1d39c94Port">
<operation name="getHrDeviceErrors" parameterOrder="index">
    <input message="getHrDeviceErrorsRequest"/>
    <output message="getHrDeviceErrorsResponse"/>
</operation>
<operation name="getHrDeviceID" parameterOrder="index">
    <input message="getHrDeviceIDRequest"/>
    <output message="getHrDeviceIDResponse"/>
</operation>
<operation name="getHrDeviceStatus" parameterOrder="index">
    <input message="getHrDeviceStatusRequest"/>
    <output message="getHrDeviceStatusResponse"/>
</operation>
<operation name="getHrDeviceType" parameterOrder="index">
    <input message="getHrDeviceTypeRequest"/>
    <output message="getHrDeviceTypeResponse"/>
</operation>
<operation name="getHrDeviceDescr" parameterOrder="index">
    <input message="getHrDeviceDescrRequest"/>
    <output message="getHrDeviceDescrResponse"/>
</operation>

</portType>
```

Listing 5.5: *hrDeviceEntry* WSDL: operations

be useful, some generic operations need to be provided for object and instance management.

The principle of defining accessor operations for each attribute in the class diagram, is a standard option in ArcStyler. For each attribute can be specified whether they should be "Web service enabled" and accessors can automatically be generated for a certain target platform. This is specified by adding marks to the model. In this case, marks are added for deployment on a Java-based platform, thus setting the mark "GenAccessors" (generate accessors) to true works only when Java code is generated. "Web service enabled" is part of the "Web service" marks pane and this results in the accessors being added to a generated WSDL definition.

When these steps are taken for each class, ArcStyler can generate Java classes and a WSDL definition for it. The generated Java classes need further implementation of the defined operations, before they can be tested in the built-in Jakarta Tomcat web server [103]. One first problem is already that the generated WSDL definition is not always readable and not always correct. First of all, it contains very obscure names for bindings and porttypes (interfaces in WSDL 2.0) like:

```
com.io_software.catools.cmod.cmod.foundationJMIImpl.
  CAClassImpl1d39c94Binding
```

Second, syntax errors are present (twice "http://"), although in this example it is the only syntax error found.

```
xmlns:soap="http://http://schemas.xmlsoap.org/wsdl/soap/"
```

And there are several occurrences of "TODO" comments as well. Listing 5.5 presents the generated WSDL definition of the operations of the *hrDeviceEntry* class are given.

```
<message name="getHrDeviceErrorsRequest">
  <part name="index" type="int"/>
</message>
<message name="getHrDeviceErrorsResponse">
  <part name="index" type="int"/>
</message>

<message name="getHrDeviceIDRequest">
  <part name="index" type="int"/>
</message>
<message name="getHrDeviceIDResponse">
  <part name="index" type="int"/>
</message>

<message name="getHrDeviceStatusRequest">
  <part name="index" type="int"/>
</message>
<message name="getHrDeviceStatusResponse">
  <part name="index" type="int"/>
</message>

<message name="getHrDeviceTypeRequest">
  <part name="index" type="int"/>
</message>
<message name="getHrDeviceTypeResponse">
  <part name="index" type="int"/>
</message>

<message name="getHrDeviceDescrRequest">
  <part name="index" type="int"/>
</message>
<message name="getHrDeviceDescrResponse">
  <part name="index" type="int"/>
</message>

</portType>
```

Listing 5.6: *hrDeviceEntry* WSDL: messages

Message structure

For describing the message structure, the example of the *hrDeviceEntry* class will also be used here. It reveals a more serious problem of the way ArcStyler generates WSDL messages: it does not differentiate between request and response message parts for a certain operation. This means that a request message contains the same parts as a response message for an operation, regardless of whether operation parameters are defined as *in*, *out*, or *in-out*. It also does not reuse existing messages with a same structure for different operations. This can be seen in listing 5.6 where the WSDL definition of the messages in the *hrDeviceEntry* class are given.

The complete WSDL definition for the *hrDeviceEntry* can be found in appendix H.

5.3.3 Summary

ArcStyler appears quite useful for creating a Web service based on a UML class diagram. There are many possibilities for marking the model and it has built-in support to create Web services for the Java and .NET platforms. However, it does not generate clean WSDL files, so they need manual modification. But the creation of the Web service itself is very easy. Apart from the fact that functionality of operations need to be implemented manually, the generated

Web service can directly be used. It has a built-in Jakarta Tomcat web server which makes it very easy to test a Web service under development.

Of course, this presents a limited view of MDA tool usage, since only ArcStyler is tested. Even though ArcStyler currently regards itself as being the most advanced MDA tool available, Objecteering is an interesting candidate as well. It could prove to be useful to also test this tool for its usability with generating Web services. A comparison of these two tools can be found in [22].

Chapter 6

Conclusions

The conclusions of this thesis are divided into two parts. Firstly, section 6.1 presents the main contributions of this thesis with answers to the research questions. Finally, section 6.2 presents several ideas for future work.

6.1 Main contributions

This section gives the main contribution of the thesis. The research questions from section 1.3 are repeated here (in bold), and for each question an answer will be given. These answers will contain references to the previous chapters where they are explained.

Why are Web services suitable to use for management of IP networks?

This thesis has shown how Web services can be applied for network management, based on ideas from SNMP. The following list shows several similarities they share (section 3.1):

- SNMP is based on the manager/agent paradigm and Web service uses the very similar concepts service provider and service requester.
- The SNMP protocol defines the operations and message structure. With Web service this can be achieved in a WSDL definition.
- Operations are invoked and the results are returned through the exchange of pre-defined messages.
- With Web services it is possible to provide the same type of operations as SNMP, though it provides possibilities for much richer operations.

There are also a number of differences that can be distinguished:

- Web services is a generic technology and not defined specifically for network management like SNMP. Therefore it is expected that more developers and users will be familiar with Web service concepts and be able to easily apply them for network management (section 3.1).

- SNMP uses UDP as its underlying transport protocol, whereas Web services uses TCP (with HTTP, SMTP, FTP, etc. in between). UDP is considered to perform better in case of network congestion and TCP when large amounts of data need to be transported. More experience with TCP-based network management should point out which protocol is more valuable for network management (section 3.1).

- Basically SNMP distinguishes three message exchange patterns (request-response, trap, notification), where Web services does not impose a certain pattern. WSDL does define message exchange patterns that may be used in the definition of operation, though it is not mandatory to adhere to them (section 3.2).

- In contrast with SNMP, a Web service exposes its operations through interfaces and provides a possibility for extending them. This idea has also been recognised in the WSMF (see section). Suppose a vendor has implemented a Web service interface on a networked device with standardised operations. It is possible for this vendor to provide another interface that extends the standardised interface, making it possible to offer specific operations on a particular networked device while still adhering to the network management standard (section 3.3).

- Security (authentication, authorisation, encryption) is an inherent part of SNMP (version 3) and with Web services this requires the use of additional standards. However, Web services (will) provide many more additional standards covering transactions, choreography, reliability of messaging, etc. Some of these (most notably transactions) are in principle not possible with SNMP at all. The main disadvantage right now is that most of these additional standards are rather immature and developing rapidly, which does not make it easy to develop applications unless they are updated frequently. Furthermore there are several additional standards that try to solve a similar problem, like both WS-transactions and BPEL offer transactional functionality. It remains a matter of time to know which initiative is most viable (section 3.4).

Summarising, Web services provide some very similar characteristics compared to SNMP and therefore they can be considered to be suitable to use for network management. Web services have some distinct differences with SNMP as well, some of which can be regarded as an advantage for Web service, like the expectance that Web services will be widely used and additional standards that Web services (will) provide (mainly transactions, since this is just not possible with SNMP).

What needs to be standardised for Web services-based network management?

This thesis proposes that standardisation of Web services for network management should take place by standardising only the abstract interface definition (section 4.1). This includes the interfaces, operations, message structure and types, but **not** the binding. The binding could possibly be standardised separately, thus providing a default messaging protocol and encoding. All these parts can be separated (stored in separate WSDL documents) from the service definition, making use of the modularity of WSDL.

What possible forms can management operations take and what are their merits?

Two degrees of freedom are distinguished when discussing management operations: operation granularity and parameter transparency (section 4.2). For standardisation one can vary between very coarse-grained to very fine-grained operations, as well as transparent and non-transparent parameters.

Non-transparent parameters:

- are defined at WSDL level. If the (structure of) management information changes, the WSDL definition has to change accordingly.
- require no higher level data definition schema. This can make operations be easily used in generic applications such as spreadsheets or word-processors.

Transparent parameters:

- are abstracted from protocol level, which could be more flexible with regard to modifications to management information.
- need a higher-level (XML) schema for the definition of data. This also requires an XML-parser or other kind of data-parser.
- are probably most interesting for more skilled users or specific management applications. For instance, passing XML schema's to an operation and validating it, is harder to accomplish in a generic tool.

Coarse-grained operations:

- are limited in number. There should be very few coarse-grained operations to provide management services, which can keep WSDL definitions simple and small. Users only need to understand a few operations, but possibly more complicated parameters.
- are likely to be more difficult to implementation.
- are expected to be used for Web services by main players in the industry. Standard objects in programming language can offer many operations with limited functionality, while distributed objects are more likely to offer higher-level, complex functionality.

Fine-grained operations:

- could result in many operations with limited functionality. One can question its usefulness in a distributed environment.
- can be easier understood and used in generic tools and home users. For instance, specific operations for each type of management information can very easily be used in a spreadsheet.

It is expected that choices between all these alternatives will most likely be a trade-off between simplicity and expressiveness. It is very much dependent on how future usage of management operations are envisioned. One should definitely keep in mind that it is very easy to standardise a few operations, where proprietary extensions can be made using the interface extensibility.

Which role can MDA tools play for developing Web Services-based management applications?

MDA seems very promising in the field of software engineering and Web services in particular. When management information is comprised in models and both management applications and servers need to be implemented on a wide variety of platforms (each networked device can theoretically be a different platform), the usage of MDA is evident.

The problem is that MDA seems to be just in the beginning stages of its development. One of the most elaborate MDA tools (ArcStyler) was used to gain experience with this and for now, it remains not much more than a code generation tool that can create a skeleton of the application for a certain platform (section 5.3). In order for tools to be really useful, there should be models for many types of platforms where management applications are intended to run on. It also requires the definitions for model transformation, that can translate the management information models and operation definitions to platform specific models. When tools allow this, it should certainly be an area of further research. Of course, model transformation can also be done by hand, but that undermines the added value of an MDA tool.

6.2 Future work

This thesis presents some approaches of how Web services can be created and deployed, but there is no experience gained with working implementations of them. This is a very important topic of further research. Furthermore, based on the discussion on operation granularity and parameter transparency (section 4.2) there needs to be more clarity on which kind of operations are really useful and who the intended users of network management Web services are. Therefore it is important to gain experience with implementations that offer a variety of operations (coarse-grained to fine-grained) and parameters (transparent to non-transparent).

Also the usefulness of a certain information model should be recognised. Since it seems fairly simple to create an ER diagram of MIB definitions (although it is worth to check this with more existing MIBs), it remains to be seen whether this is a suitable information model, compared to object-oriented UML class diagrams. And although ER diagrams are presented here, they have not been used for implementation purposes and moreover, they are also not used in ArcStyler.

WSDL documents can be regarded as a task-oriented data model 4.3.2 and it could therefore be interesting to see if and how a WSDL definition can lead to a task-oriented information model. If this is possible using an MDA tool (PSM to PIM transformation, if WSDL is regarded as a PSM), a WSDL version-independent could possibly be standardised. And whenever the WSDL standards change (including additional standards), only the PIM to PSM transformation needs to be changed once.

Appendix A

SNMPv2-PDU definitions

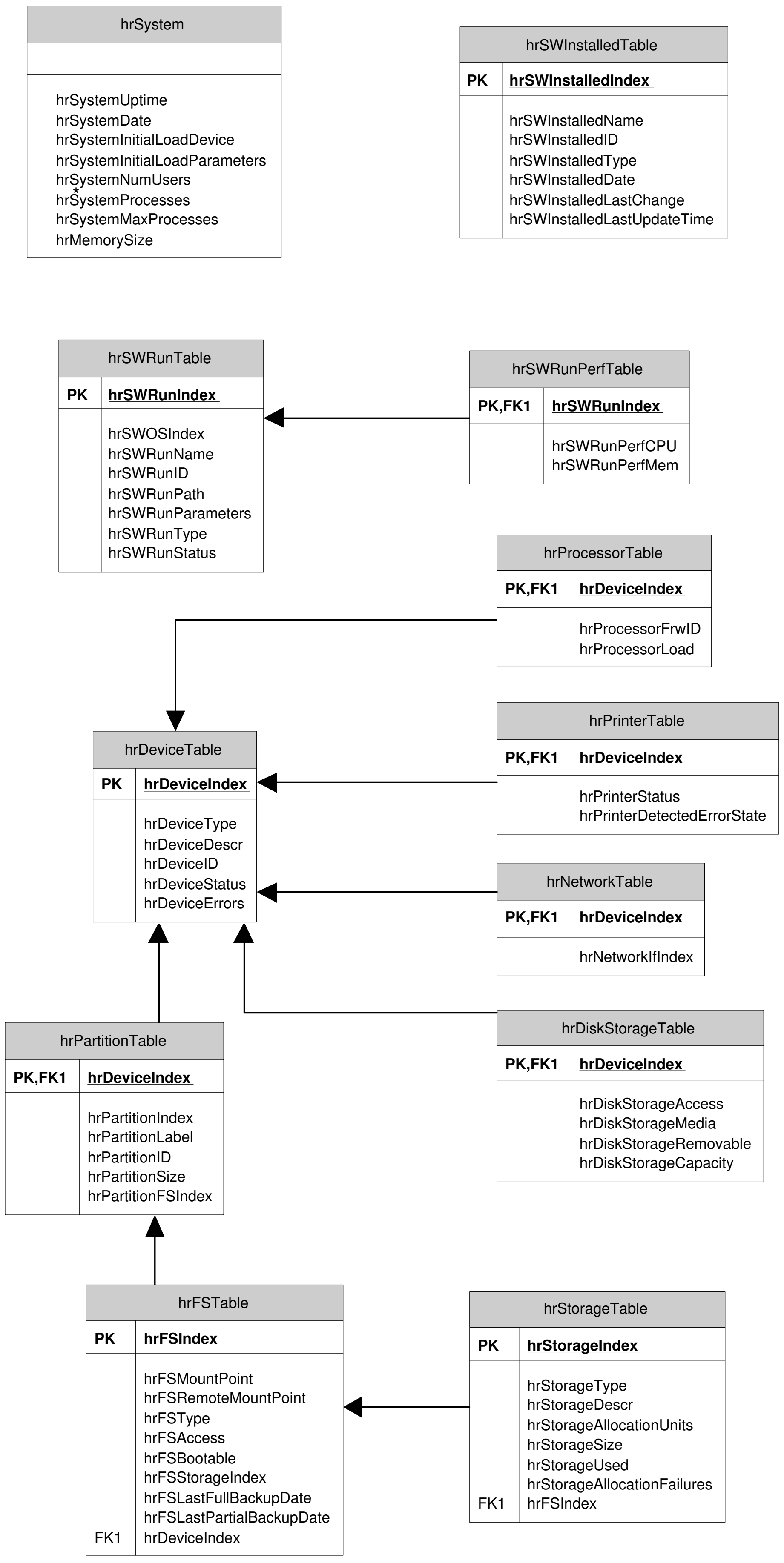
```
SNMPv2−PDU DEFINITIONS ::= BEGIN

ObjectName ::= OBJECT IDENTIFIER

ObjectSyntax ::= CHOICE {
        simple SimpleSyntax,
        application−wide ApplicationSyntax }

SimpleSyntax ::= CHOICE {
        integer−value INTEGER (−2147483648..2147483647),
        string−value OCTET STRING (SIZE (0..65535)),
        objectID−value OBJECT IDENTIFIER }

ApplicationSyntax ::= CHOICE {
        ipAddress−value IpAddress,
        counter−value Counter32,
        timeticks−value TimeTicks,
        arbitrary−value Opaque,
        big−counter−value Counter64,
        unsigned−integer−value Unsigned32 }

IpAddress ::= [APPLICATION 0] IMPLICIT OCTET STRING (SIZE (4))

Counter32 ::= [APPLICATION 1] IMPLICIT INTEGER (0..4294967295)

Unsigned32 ::= [APPLICATION 2] IMPLICIT INTEGER (0..4294967295)

Gauge32 ::= Unsigned32

TimeTicks ::= [APPLICATION 3] IMPLICIT INTEGER (0..4294967295)

Opaque ::= [APPLICATION 4] IMPLICIT OCTET STRING

Counter64 ::= [APPLICATION 6]
              IMPLICIT INTEGER (0..18446744073709551615)

−− protocol data units

PDUs ::= CHOICE {
     get−request GetRequest−PDU,
     get−next−request GetNextRequest−PDU,
     get−bulk−request GetBulkRequest−PDU,
     response Response−PDU,
     set−request SetRequest−PDU,
     inform−request InformRequest−PDU,
     snmpV2−trap SNMPv2−Trap−PDU,
     report Report−PDU }

−− PDUs

GetRequest−PDU ::= [0] IMPLICIT PDU
```

```
GetNextRequest−PDU ::= [1] IMPLICIT PDU

Response−PDU ::= [2] IMPLICIT PDU

SetRequest−PDU ::= [3] IMPLICIT PDU

−− [4] is obsolete

GetBulkRequest−PDU ::= [5] IMPLICIT BulkPDU

InformRequest−PDU ::= [6] IMPLICIT PDU

SNMPv2−Trap−PDU ::= [7] IMPLICIT PDU

−− Usage and precise semantics of Report−PDU are not defined
−− in this document. Any SNMP administrative framework making
−− use of this PDU must define its usage and semantics.

Report−PDU ::= [8] IMPLICIT PDU

max−bindings INTEGER ::= 2147483647

PDU ::= SEQUENCE {
        request−id INTEGER (−214783648..214783647),

        error−status −− sometimes ignored
            INTEGER {
                noError(0),
                tooBig(1),
                noSuchName(2), −− for proxy compatibility
                badValue(3), −− for proxy compatibility
                readOnly(4), −− for proxy compatibility
                genErr(5),
                noAccess(6),
                wrongType(7),
                wrongLength(8),
                wrongEncoding(9),
                wrongValue(10),
                noCreation(11),
                inconsistentValue(12),
                resourceUnavailable(13),
                commitFailed(14),
                undoFailed(15),
                authorizationError(16),
                notWritable(17),
                inconsistentName(18)
            },

        error−index −− sometimes ignored
            INTEGER (0..max−bindings),

        variable−bindings −− values are sometimes ignored
            VarBindList
    }

BulkPDU ::= −− must be identical in
    SEQUENCE { −− structure to PDU
        request−id INTEGER (−214783648..214783647),
        non−repeaters INTEGER (0..max−bindings),
        max−repetitions INTEGER (0..max−bindings),

        variable−bindings −− values are ignored
            VarBindList
    }

−− variable binding

VarBind ::= SEQUENCE {
        name ObjectName,

        CHOICE {
            value ObjectSyntax,
            unSpecified NULL, −− in retrieval requests
```

```
                                             −− exceptions in responses
               noSuchObject [0] IMPLICIT NULL,
               noSuchInstance [1] IMPLICIT NULL,
               endOfMibView [2] IMPLICIT NULL
          }
     }

−− variable−binding list

VarBindList ::= SEQUENCE (SIZE (0..max−bindings)) OF VarBind

END
```

Appendix B

Host-resources database model diagram


hrSystem
hrSystemUptime
hrSystemDate
hrSystemInitialLoadDevice
hrSystemInitialLoadParameters
hrSystemNumUsers
hrSystemProcesses
hrSystemMaxProcesses
hrMemorySize
hrSWInstalledTable
PK hrSWInstalledIndex
hrSWInstalledName
hrSWInstalledID
hrSWInstalledType
hrSWInstalledDate
hrSWInstalledLastChange
hrSWInstalledLastUpdateTime
hrSWRunTable
PK hrSWRunIndex
hrSWOSIndex
hrSWRunName
hrSWRunID
hrSWRunPath
hrSWRunParameters
hrSWRunType
hrSWRunStatus
hrSWRunPerfTable
PK,FK1 hrSWRunIndex
hrSWRunPerfCPU
hrSWRunPerfMem
hrProcessorTable
PK,FK1 hrDeviceIndex
hrProcessorFrwID
hrProcessorLoad
hrDeviceTable
PK hrDeviceIndex
hrDeviceType
hrDeviceDescr
hrDeviceID
hrDeviceStatus
hrDeviceErrors
hrPrinterTable
PK,FK1 hrDeviceIndex
hrPrinterStatus
hrPrinterDetectedErrorState
hrNetworkTable
PK,FK1 hrDeviceIndex
hrNetworkIfIndex
hrPartitionTable
PK,FK1 hrDeviceIndex
hrPartitionIndex
hrPartitionLabel
hrPartitionID
hrPartitionSize
hrPartitionFSIndex
hrDiskStorageTable
PK,FK1 hrDeviceIndex
hrDiskStorageAccess
hrDiskStorageMedia
hrDiskStorageRemovable
hrDiskStorageCapacity
hrFSTable
PK hrFSIndex
hrFSMountPoint
hrFSRemoteMountPoint
hrFSType
hrFSAccess
hrFSBootable
hrFSStorageIndex
hrFSLastFullBackupDate
hrFSLastPartialBackupDate
FK1 hrDeviceIndex
hrStorageTable
PK hrStorageIndex
hrStorageType
hrStorageDescr
hrStorageAllocationUnits
hrStorageSize
hrStorageUsed
hrStorageAllocationFailures
FK1 hrFSIndex

Appendix C

SNMP-WS abstract interface definition

```
<?xml version="1.0" encoding="UTF-8"?>
<definitions name="snmp-simple"
             targetNamespace="http://www.example.org/snmp-simple.wsdl"
             xmlns="http://schemas.xmlsoap.org/wsdl/"
             xmlns:mime="http://schemas.xmlsoap.org/wsdl/mime/"
             xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
             xmlns:tns="http://www.example.org/snmp-simple.wsdl"
             xmlns:xsd="http://www.w3.org/2001/XMLSchema"
             xmlns:xsd1="http://www.example.org/snmp-simple.xsd">

    <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">
        SNMP simplified messages and operations
    </documentation>


    <types>
        <xsd:schema targetNamespace="http://www.example.org/snmp-simple.xsd"
                    xmlns:SOAP-ENC="http://schemas.xmlsoap.org/soap/encoding/"
                    xmlns:xsd="http://www.w3.org/2001/XMLSchema"
                    xmlns:xsd1="http://www.example.org/snmp-simple.xsd">
            <xsd:import namespace="http://www.example.org/snmp-simple.xsd"
                        schemaLocation="snmp-simple.xsd"/>
        </xsd:schema>
    </types>


    <message name="requestMessage">
        <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">SNMPv2 request
              message</documentation>
        <part name="variable-binding" type="xsd1:VarBindList"/>
    </message>
    <message name="responseMessage">
        <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">SNMPv2 response
              message</documentation>
        <part name="variable-binding" type="xsd1:VarBindList"/>
    </message>
    <message name="get-bulkRequest">
        <part name="non-repeaters" type="xsd:int"/>
        <part name="max-repetitions" type="xsd:int"/>
        <part name="variable-binding" type="xsd1:VarBindList"/>
    </message>
    <message name="trapMessage">
        <part name="sysUpTime" type="xsd1:ObjectName"/>
        <part name="snmpTrapOID" type="xsd1:ObjectName"/>
        <part name="variable-binding" type="xsd1:VarBindList"/>
    </message>
    <message name="errorMessage">
        <part name="error-status" type="xsd1:error-status"/>
    </message>


    <portType name="snmp−simplePortType">
        <operation name="get">
            <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">manager to agent
                communication</documentation>
            <input message="tns:requestMessage"/>
            <output message="tns:responseMessage"/>
            <fault message="tns:errorMessage" name="error−status"/>
        </operation>
        <operation name="get−next">
            <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">manager to agent
                communication</documentation>
            <input message="tns:requestMessage"/>
            <output message="tns:responseMessage"/>
            <fault message="tns:errorMessage" name="error−status"/>
        </operation>
        <operation name="set">
            <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">manager to agent
                communication</documentation>
            <input message="tns:requestMessage"/>
            <output message="tns:responseMessage"/>
            <fault message="tns:errorMessage" name="error−status"/>
        </operation>
        <operation
            name="get−bulk"
            parameterOrder="non−repeaters␣max−repetitions␣variable−binding">
            <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">manager to agent
                communication</documentation>
            <input message="tns:get−bulkRequest"/>
            <output message="tns:responseMessage"/>
            <fault message="tns:errorMessage" name="error−status"/>
        </operation>
        <operation name="trap">
            <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">agent to manager
                communication</documentation>
            <output message="tns:trapMessage"/>
        </operation>
        <operation name="inform">
            <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">manager to
                manager communication</documentation>
            <input message="tns:trapMessage"/>
            <output message="tns:responseMessage"/>
            <fault message="tns:errorMessage" name="error−status"/>
        </operation>
    </portType>

</definitions>
```

Appendix D

SNMP-WS binding definition

```
<?xml version="1.0" encoding="UTF-8"?>
<definitions name="snmp-simple"
                targetNamespace="http://www.example.org/snmp-simple.wsdl"
                xmlns="http://schemas.xmlsoap.org/wsdl/"
                xmlns:mime="http://schemas.xmlsoap.org/wsdl/mime/"
                xmlns:soap="http://schemas.xmlsoap.org/wsdl/soap/"
                xmlns:tns="http://www.example.org/snmp-simple.wsdl"
                xmlns:xsd="http://www.w3.org/2001/XMLSchema"
                xmlns:xsd1="http://www.example.org/snmp-simple.xsd">

    <documentation xmlns:wsdl="http://schemas.xmlsoap.org/wsdl/">
        SOAP binding to SNMP abstract interface definition (SNMPv2 operations)
    </documentation>

    <import location="snmp-simple_abstract-interface.wsdl"
              namespace="http://www.example.org/snmp-simple.wsdl"/>

    <binding name="snmp-simpleBinding" type="tns:snmp-simplePortType">
        <soap:binding style="rpc" transport="http://schemas.xmlsoap.org/soap/http"/>
        <operation name="get">
            <soap:operation soapAction="snmp-simple:snmp-simplePortType#get"/>
            <input>
                <soap:body parts="variable-binding" use="literal"/>
            </input>
            <output>
                <soap:body parts="variable-binding" use="literal"/>
            </output>
            <fault name="error-status">
                <soap:fault name="error-status" use="literal"/>
            </fault>
        </operation>
        <operation name="get-next">
            <soap:operation soapAction="snmp-simple:snmp-simplePortType#get-next"/>
            <input>
                <soap:body parts="variable-binding" use="literal"/>
            </input>
            <output>
                <soap:body parts="variable-binding" use="literal"/>
            </output>
            <fault name="error-status">
                <soap:fault name="error-status" use="literal"/>
            </fault>
        </operation>
        <operation name="set">
            <soap:operation soapAction="snmp-simple:snmp-simplePortType#set"/>
            <input>
                <soap:body parts="variable-binding" use="literal"/>
            </input>
            <output>
                <soap:body parts="variable-binding" use="literal"/>
            </output>
            <fault name="error−status">
                <soap:fault name="error−status" use="literal"/>
            </fault>
        </operation>
        <operation name="get−bulk">
            <soap:operation soapAction="snmp−simple:snmp−simplePortType#get−bulk"/>
            <input>
                <soap:body parts="max−repetitions␣non−repeaters␣variable−binding" use="
                     literal"/>
            </input>
            <output>
                <soap:body parts="variable−binding" use="literal"/>
            </output>
            <fault name="error−status">
                <soap:fault name="error−status" use="literal"/>
            </fault>
        </operation>
        <operation name="trap">
            <soap:operation soapAction="snmp−simple:snmp−simplePortType#trap"/>
            <output>
                <soap:body parts="snmpTrapOID␣sysUpTime␣variable−binding" use="literal"/
                     >
            </output>
        </operation>
        <operation name="inform">
            <soap:operation soapAction="snmp−simple:snmp−simplePortType#inform"/>
            <input>
                <soap:body parts="snmpTrapOID␣sysUpTime␣variable−binding" use="literal"/
                     >
            </input>
            <output>
                <soap:body parts="variable−binding" use="literal"/>
            </output>
            <fault name="error−status">
                <soap:fault name="error−status" use="literal"/>
            </fault>
        </operation>
    </binding>
</definitions>
```

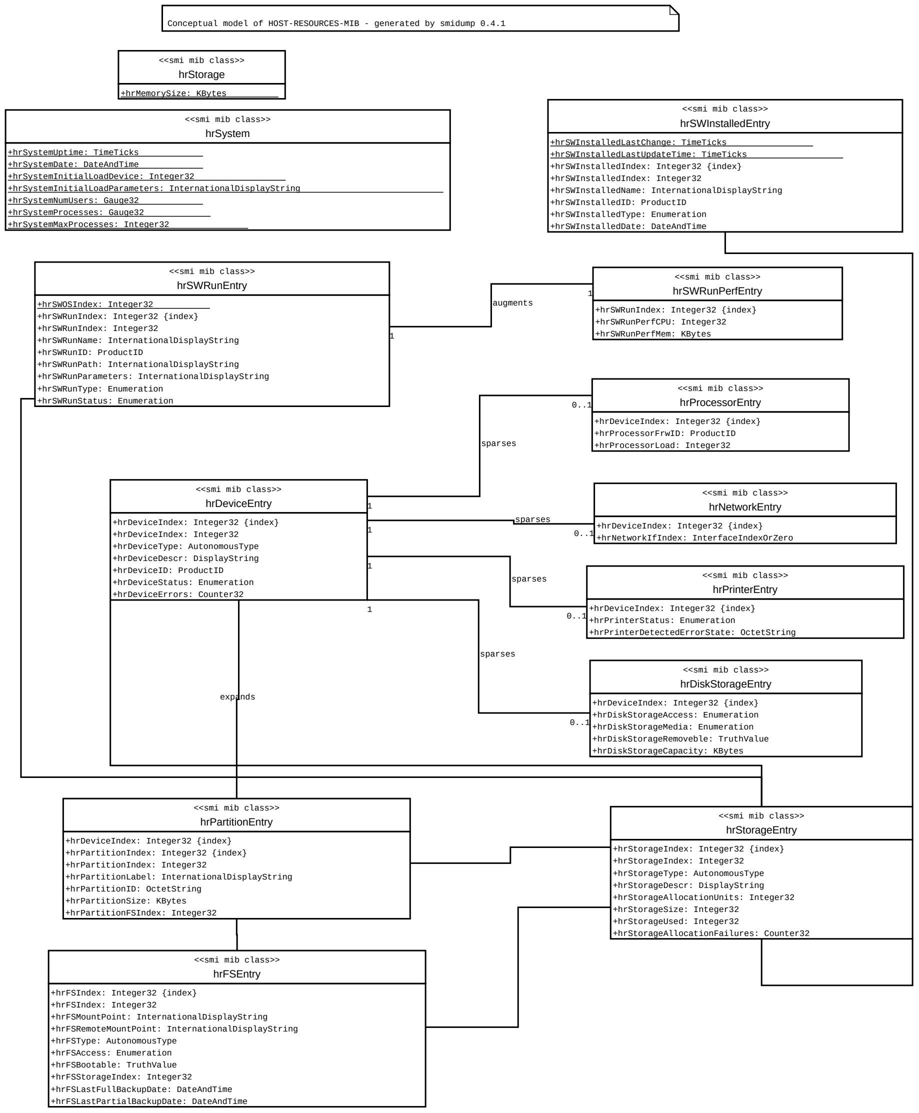
Appendix E

snmp-simple.xsd

```
<?xml version="1.0" encoding="UTF-8"?>
<!DOCTYPE schema SYSTEM "http://www.w3.org/2001/XMLSchema.dtd">

<xsd:schema targetNamespace="http://www.example.org/snmp-simple.xsd"
            xmlns:SOAP-ENC="http://schemas.xmlsoap.org/soap/encoding/"
            xmlns:xsd="http://www.w3.org/2001/XMLSchema"
            xmlns:xsd1="http://www.example.org/snmp-simple.xsd">

    <xsd:simpleType name="error-status">
        <xsd:restriction base="xsd:string">
            <xsd:enumeration value="noError"/>
            <xsd:enumeration value="tooBig"/>
            <xsd:enumeration value="noSuchName"/>
            <xsd:enumeration value="badValue"/>
            <xsd:enumeration value="readOnly"/>
            <xsd:enumeration value="genError"/>
            <xsd:enumeration value="noAccess"/>
            <xsd:enumeration value="wrongType"/>
            <xsd:enumeration value="wrongLength"/>
            <xsd:enumeration value="wrongEncoding"/>
            <xsd:enumeration value="wrongValue"/>
            <xsd:enumeration value="noCreation"/>
            <xsd:enumeration value="inconsistentValue"/>
            <xsd:enumeration value="resourceUnavailable"/>
            <xsd:enumeration value="commitFailed"/>
            <xsd:enumeration value="undoFailed"/>
            <xsd:enumeration value="authorizationError"/>
            <xsd:enumeration value="notWritable"/>
            <xsd:enumeration value="inconsistentName"/>
        </xsd:restriction>
    </xsd:simpleType>

    <xsd:complexType name="VarBindList">
        <xsd:sequence>
            <xsd:element maxOccurs="unbounded" minOccurs="0" name="varbind" type="
                xsd1:VarBind"/>
        </xsd:sequence>
    </xsd:complexType>

    <xsd:complexType name="VarBind">
        <xsd:sequence>
            <xsd:element maxOccurs="1" minOccurs="1" name="name" type="
                xsd1:ObjectName"/>
            <xsd:choice>
                <xsd:element name="value" type="xsd:string"/>
                <xsd:element name="unspecified" type="xsd:string"/>
                <xsd:element name="noSuchObject" type="xsd:string"/>
                <xsd:element name="noSuchInstance" type="xsd:string"/>
                <xsd:element name="endOfMibView" type="xsd:string"/>
            </xsd:choice>
        </xsd:sequence>
    </xsd:complexType>

    <xsd:simpleType name="ObjectName">
        <xsd:restriction base="xsd:string"/>
    </xsd:simpleType>

</xsd:schema>
```

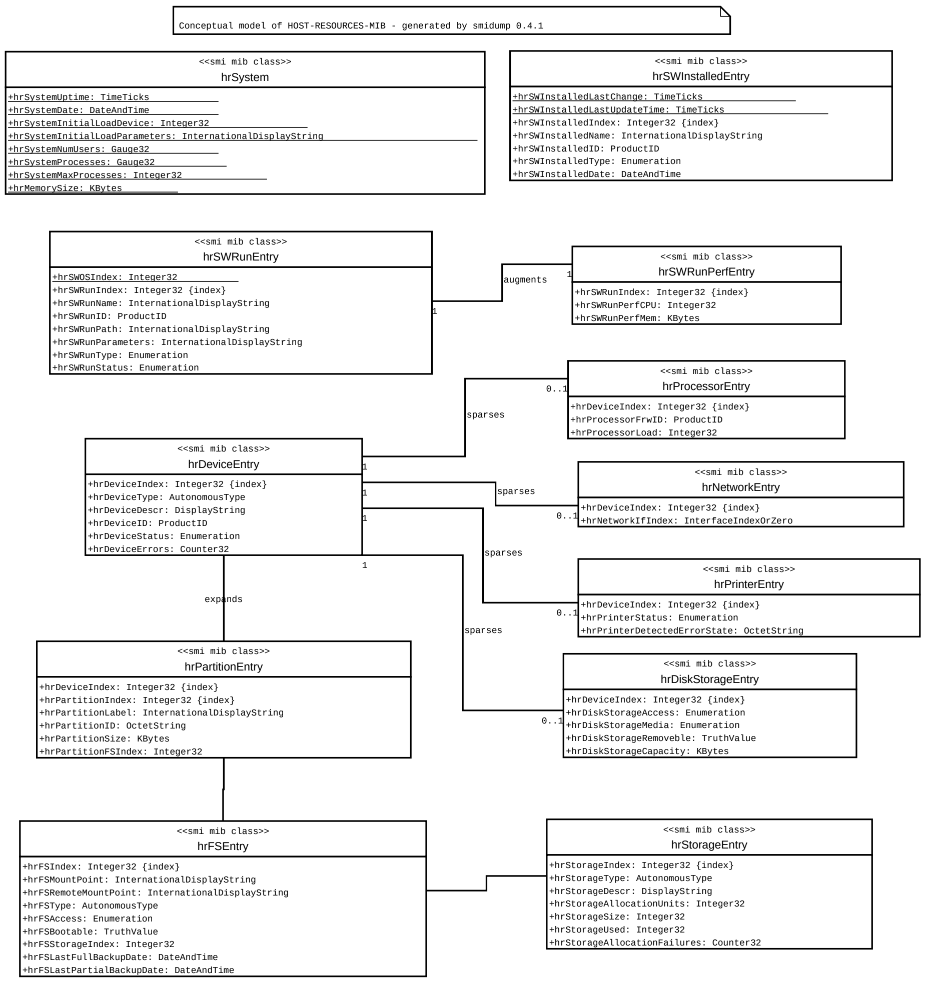
Appendix F

Generated Host-Resources UML class diagram


Conceptual model of HOST-RESOURCES-MIB - generated by smidump 0.4.1
<<smi mib class>>
hrStorage
+hrMemorySize: KBytes
<<smi mib class>>
hrSystem
+hrSystemUptime: TimeTicks
+hrSystemDate: DateAndTime
+hrSystemInitialLoadDevice: Integer32
+hrSystemInitialLoadParameters: InternationalDisplayString
+hrSystemNumUsers: Gauge32
+hrSystemProcesses: Gauge32
+hrSystemMaxProcesses: Integer32
<<smi mib class>>
hrSWInstalledEntry
+hrSWInstalledLastChange: TimeTicks
+hrSWInstalledLastUpdateTime: TimeTicks
+hrSWInstalledIndex: Integer32 {index}
+hrSWInstalledIndex: Integer32
+hrSWInstalledName: InternationalDisplayString
+hrSWInstalledID: ProductID
+hrSWInstalledType: Enumeration
+hrSWInstalledDate: DateAndTime
<<smi mib class>>
hrSWRunEntry
+hrSWOSIndex: Integer32
+hrSWRunIndex: Integer32 {index}
+hrSWRunIndex: Integer32
+hrSWRunName: InternationalDisplayString
+hrSWRunID: ProductID
+hrSWRunPath: InternationalDisplayString
+hrSWRunParameters: InternationalDisplayString
+hrSWRunType: Enumeration
+hrSWRunStatus: Enumeration
augments
1
1
<<smi mib class>>
hrSWRunPerfEntry
+hrSWRunIndex: Integer32 {index}
+hrSWRunPerfCPU: Integer32
+hrSWRunPerfMem: KBytes
<<smi mib class>>
hrProcessorEntry
+hrDeviceIndex: Integer32 {index}
+hrProcessorFrwID: ProductID
+hrProcessorLoad: Integer32
0..1
sparses
<<smi mib class>>
hrDeviceEntry
+hrDeviceIndex: Integer32 {index}
+hrDeviceIndex: Integer32
+hrDeviceType: AutonomousType
+hrDeviceDescr: DisplayString
+hrDeviceID: ProductID
+hrDeviceStatus: Enumeration
+hrDeviceErrors: Counter32
1
1
1
1
sparses
0..1
<<smi mib class>>
hrNetworkEntry
+hrDeviceIndex: Integer32 {index}
+hrNetworkIfIndex: InterfaceIndexOrZero
sparses
0..1
<<smi mib class>>
hrPrinterEntry
+hrDeviceIndex: Integer32 {index}
+hrPrinterStatus: Enumeration
+hrPrinterDetectedErrorState: OctetString
sparses
0..1
<<smi mib class>>
hrDiskStorageEntry
+hrDeviceIndex: Integer32 {index}
+hrDiskStorageAccess: Enumeration
+hrDiskStorageMedia: Enumeration
+hrDiskStorageRemoveble: TruthValue
+hrDiskStorageCapacity: KBytes
expands
<<smi mib class>>
hrPartitionEntry
+hrDeviceIndex: Integer32 {index}
+hrPartitionIndex: Integer32 {index}
+hrPartitionIndex: Integer32
+hrPartitionLabel: InternationalDisplayString
+hrPartitionID: OctetString
+hrPartitionSize: KBytes
+hrPartitionFSIndex: Integer32
<<smi mib class>>
hrStorageEntry
+hrStorageIndex: Integer32 {index}
+hrStorageIndex: Integer32
+hrStorageType: AutonomousType
+hrStorageDescr: DisplayString
+hrStorageAllocationUnits: Integer32
+hrStorageSize: Integer32
+hrStorageUsed: Integer32
+hrStorageAllocationFailures: Counter32
<<smi mib class>>
hrFSEntry
+hrFSIndex: Integer32 {index}
+hrFSIndex: Integer32
+hrFSMountPoint: InternationalDisplayString
+hrFSRemoteMountPoint: InternationalDisplayString
+hrFSType: AutonomousType
+hrFSAccess: Enumeration
+hrFSBootable: TruthValue
+hrFSStorageIndex: Integer32
+hrFSLastFullBackupDate: DateAndTime
+hrFSLastPartialBackupDate: DateAndTime

Appendix G

Revised Host-Resources UML class diagram


Conceptual model of HOST-RESOURCES-MIB - generated by smidump 0.4.1
<<smi mib class>>
hrSystem
+hrSystemUptime: TimeTicks
+hrSystemDate: DateAndTime
+hrSystemInitialLoadDevice: Integer32
+hrSystemInitialLoadParameters: InternationalDisplayString
+hrSystemNumUsers: Gauge32
+hrSystemProcesses: Gauge32
+hrSystemMaxProcesses: Integer32
+hrMemorySize: KBytes
<<smi mib class>>
hrSWInstalledEntry
+hrSWInstalledLastChange: TimeTicks
+hrSWInstalledLastUpdateTime: TimeTicks
+hrSWInstalledIndex: Integer32 {index}
+hrSWInstalledName: InternationalDisplayString
+hrSWInstalledID: ProductID
+hrSWInstalledType: Enumeration
+hrSWInstalledDate: DateAndTime
<<smi mib class>>
hrSWRunEntry
+hrSWOSIndex: Integer32
+hrSWRunIndex: Integer32 {index}
+hrSWRunName: InternationalDisplayString
+hrSWRunID: ProductID
+hrSWRunPath: InternationalDisplayString
+hrSWRunParameters: InternationalDisplayString
+hrSWRunType: Enumeration
+hrSWRunStatus: Enumeration
augments
1
1
<<smi mib class>>
hrSWRunPerfEntry
+hrSWRunIndex: Integer32 {index}
+hrSWRunPerfCPU: Integer32
+hrSWRunPerfMem: KBytes
<<smi mib class>>
hrProcessorEntry
+hrDeviceIndex: Integer32 {index}
+hrProcessorFrwID: ProductID
+hrProcessorLoad: Integer32
0..1
sparses
<<smi mib class>>
hrDeviceEntry
+hrDeviceIndex: Integer32 {index}
+hrDeviceType: AutonomousType
+hrDeviceDescr: DisplayString
+hrDeviceID: ProductID
+hrDeviceStatus: Enumeration
+hrDeviceErrors: Counter32
1
1
1
1
sparses
<<smi mib class>>
hrNetworkEntry
+hrDeviceIndex: Integer32 {index}
+hrNetworkIfIndex: InterfaceIndexOrZero
0..1
sparses
<<smi mib class>>
hrPrinterEntry
+hrDeviceIndex: Integer32 {index}
+hrPrinterStatus: Enumeration
+hrPrinterDetectedErrorState: OctetString
0..1
sparses
expands
<<smi mib class>>
hrDiskStorageEntry
+hrDeviceIndex: Integer32 {index}
+hrDiskStorageAccess: Enumeration
+hrDiskStorageMedia: Enumeration
+hrDiskStorageRemoveble: TruthValue
+hrDiskStorageCapacity: KBytes
0..1
<<smi mib class>>
hrPartitionEntry
+hrDeviceIndex: Integer32 {index}
+hrPartitionIndex: Integer32 {index}
+hrPartitionLabel: InternationalDisplayString
+hrPartitionID: OctetString
+hrPartitionSize: KBytes
+hrPartitionFSIndex: Integer32
<<smi mib class>>
hrFSEntry
+hrFSIndex: Integer32 {index}
+hrFSMountPoint: InternationalDisplayString
+hrFSRemoteMountPoint: InternationalDisplayString
+hrFSType: AutonomousType
+hrFSAccess: Enumeration
+hrFSBootable: TruthValue
+hrFSStorageIndex: Integer32
+hrFSLastFullBackupDate: DateAndTime
+hrFSLastPartialBackupDate: DateAndTime
<<smi mib class>>
hrStorageEntry
+hrStorageIndex: Integer32 {index}
+hrStorageType: AutonomousType
+hrStorageDescr: DisplayString
+hrStorageAllocationUnits: Integer32
+hrStorageSize: Integer32
+hrStorageUsed: Integer32
+hrStorageAllocationFailures: Counter32

Appendix H

Generated WSDL for hrDeviceEntry

```
<?xml version="1.0" encoding="UTF−8"?>
<definitions name="com.io_software.catools.cmod.cmod.foundationJMIImpl.
        CAClassImpl@1d39c94"
                targetNamespace="␣"
                xmlns="http://schemas.xmlsoap.org/wsdl/"
                xmlns:soap="http://http://schemas.xmlsoap.org/wsdl/soap/"
                xmlns:xsd="http://www.w3c.org/2001/XMLSchema">
  <documentation>
      <!−−
 ! Generated by ArcStyler.
 !
 ! ArcStyler is copyrighted 1999−2003 by Interactive Objects
 ! Software GmbH. All rights reserved.
 ! http://www.ArcStyler.com/ http://www.io−software.com/
 −−>
  </documentation>


  <message name="getHrDeviceErrorsRequest">
    <part name="index" type="int"/>
  </message>
  <message name="getHrDeviceErrorsResponse">
    <part name="index" type="int"/>
  </message>

  <message name="getHrDeviceIDRequest">
    <part name="index" type="int"/>
  </message>
  <message name="getHrDeviceIDResponse">
    <part name="index" type="int"/>
  </message>

  <message name="getHrDeviceStatusRequest">
    <part name="index" type="int"/>
  </message>
  <message name="getHrDeviceStatusResponse">
    <part name="index" type="int"/>
  </message>

  <message name="getHrDeviceTypeRequest">
    <part name="index" type="int"/>
  </message>
  <message name="getHrDeviceTypeResponse">
    <part name="index" type="int"/>
  </message>

  <message name="getHrDeviceDescrRequest">
    <part name="index" type="int"/>
```

```
</message>
<message name="getHrDeviceDescrResponse">
  <part name="index" type="int"/>
</message>

<portType name="com.io_software.catools.cmod.cmod.foundationJMIImpl.
      CAClassImpl@1d39c94Port">
<operation name="getHrDeviceErrors" parameterOrder="index">
    <input message="getHrDeviceErrorsRequest"/>
    <output message="getHrDeviceErrorsResponse"/>
</operation>
<operation name="getHrDeviceID" parameterOrder="index">
    <input message="getHrDeviceIDRequest"/>
    <output message="getHrDeviceIDResponse"/>
</operation>
<operation name="getHrDeviceStatus" parameterOrder="index">
    <input message="getHrDeviceStatusRequest"/>
    <output message="getHrDeviceStatusResponse"/>
</operation>
<operation name="getHrDeviceType" parameterOrder="index">
    <input message="getHrDeviceTypeRequest"/>
    <output message="getHrDeviceTypeResponse"/>
</operation>
<operation name="getHrDeviceDescr" parameterOrder="indexaap">
    <input message="getHrDeviceDescrRequest"/>
    <output message="getHrDeviceDescrResponse"/>
</operation>

</portType>

<binding name="com.io_software.catools.cmod.cmod.foundationJMIImpl.
      CAClassImpl@1d39c94Binding" type="tns:com.io_software.catools.cmod.cmod.
      foundationJMIImpl.CAClassImpl@1d39c94Service">
  <soap:binding style="rpc" transport="http://schemas.xmlsoap.org/soap/http"/>
  <operation name="getHrDeviceErrors">
    <soap:operation soapAction="urn:host-resources-mgmt" />
    <input name="getHrDeviceErrorsRequest">
      <soap:body namespace="urn:host-resources-mgmt" use="encoded"
                encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
    </input>
    <output name="getHrDeviceErrorsResponse">
      <soap:body namespace="urn:host-resources-mgmt" use="encoded"
                encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
    </output>
  </operation>
  <operation name="getHrDeviceID">
    <soap:operation soapAction="urn:host-resources-mgmt" />
    <input name="getHrDeviceIDRequest">
      <soap:body namespace="urn:host-resources-mgmt" use="encoded"
                encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
    </input>
    <output name="getHrDeviceIDResponse">
      <soap:body namespace="urn:host-resources-mgmt" use="encoded"
                encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
    </output>
  </operation>
  <operation name="getHrDeviceStatus">
    <soap:operation soapAction="urn:host-resources-mgmt" />
    <input name="getHrDeviceStatusRequest">
      <soap:body namespace="urn:host-resources-mgmt" use="encoded"
                encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
    </input>
    <output name="getHrDeviceStatusResponse">
      <soap:body namespace="urn:host-resources-mgmt" use="encoded"
                encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
    </output>
  </operation>
  <operation name="getHrDeviceType">
    <soap:operation soapAction="urn:host-resources-mgmt" />
    <input name="getHrDeviceTypeRequest">
      <soap:body namespace="urn:host-resources-mgmt" use="encoded"
                encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
    </input>
    <output name="getHrDeviceTypeResponse">
```

```
        <soap:body namespace="urn:host−resources−mgmt" use="encoded"
                    encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
      </output>
    </operation>
    <operation name="getHrDeviceDescr">
      <soap:operation soapAction="urn:host−resources−mgmt" />
      <input name="getHrDeviceDescrRequest">
        <soap:body namespace="urn:host−resources−mgmt" use="encoded"
                    encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
      </input>
      <output name="getHrDeviceDescrResponse">
        <soap:body namespace="urn:host−resources−mgmt" use="encoded"
                    encodingStyle="http://schemas.xmlsoap.org/soap/encoding/"/>
      </output>
    </operation>

  </binding>
  <service>
    <documentation> </documentation>
    <port binding="com.io_software.catools.cmod.cmod.foundationJMIImpl.
          CAClassImpl@1d39c94Binding" name="TODO">
      <soap:adress location="http://localhost:8080/soap/servlet/rpcrouter"/>
    </port>
  </service>
</definitions>
```

Bibliography

[1] William Stallings. *SNMP, SNMPv2, SNMPv3, and RMON 1 and 2.* Addison-Wesley, Reading, MA, USA, third edition, 1999.

[2] J.P. Paulo Almeida. Web Services Development with OMG/MDA Standards. `<url:https://doc.telin.nl/dscgi/ds.py/ViewProps/File-30227>`, February 2003. WASP presentation (WASP/PM3.7).

[3] R. Frye, D. Levi, S. Routhier, and B. Wijnen. Coexistence between Version 1, Version 2, and Version 3 of the Internet-standard Network Management Framework, RFC3584. RFC 3584, Internet Engineering Task Force, August 2003.

[4] J. B. Postel. User datagram protocol. RFC 768, Internet Engineering Task Force, August 1980.

[5] Jean-Philippe Martin-Flatin. *Web-Based Management of IP Networks and Systems*. John Wiley & Sons, Ltd., Chichester, West Sussex, PO19 8SQ, England, 2003.

[6] Chris Wellens and Karl Auerbach. Towards useful management. *The Simple Times*, 4(3):1–6, July 1996.

[7] J. Schönwälder, A. Pras, and J.P. Martin-Flatin. On the future of internet management technologies. *IEEE Communications Magazine*, 41(10):90–97, October 2003.

[8] W3C: Extensible Markup Language. `<url:http://www.w3.org/XML/>`.

[9] Mi-Jung Choi, James W. Hong, and Hong-Taek Ju. XML-based Network Management for IP Networks. *ETRI Journal*, 25(6):445–463, December 2003.

[10] F. Strauß and T. Klie. Towards XML oriented internet management. In *Proc. 8th IFIP/IEEE International Symposium on Integrated Network Management*, pages 505–518, Colorado Springs, March 2003.

[11] The Internet Engineering Task Force (IETF). `<url:http://www.ietf.org>`.

[12] Network Management Research Group. `<url:http://www.ibr.cs.tu-bs.de/projects/nmrg/>`.

[13] Internet Research Task Force.
<url:http://www.irtf.org>.

[14] Internet Architecture Board.
<url:http://www.iab.org>.

[15] J. Schönwälder. Overview of the 2002 IAB Network Management Workshop, RFC3535. RFC 3535, Internet Engineering Task Force, May 2003.

[16] IETF: Evolution of SNMP Working Group.
<url:http://www.ietf.org/ietf/eos/>.

[17] IETF: Next Generation Structure of Management Information Working Group.
<url:http://www.ietf.org/ietf/sming/>.

[18] W3C: World Wide Web Consortium.
<url:http://www.w3.org>.

[19] Frank Dzubeck. Is it time to re-engineer SNMP?
<url:http://www.nwfusion.com/columnists/2004/0322dzubeck.html>, March 2004.

[20] W3C: Web Services Activity.
<url:http://www.w3.org/2002/ws/>.

[21] Object Management Group.
<url:http://www.omg.org>.

[22] Jan Willem Janssen. Evaluation of current tool support for the Model-Driven Architecture. Master's thesis, University of Twente, Enschede, The Netherlands, January 2004.

[23] Minutes of the 11th NMRG meeting, Schloss Osnabrueck, Germany.
<url:http://www.ibr.cs.tu-bs.de/projects/nmrg/minutes/minutes-011.txt>, September 2002.

[24] Jorge E. López de Vergara, Víctor A. Villagrá, Juan I. Asensio, and Julio Berrocal. Ontologies: giving semantics to network management models. *Network, IEEE*, 17(3):15– 21, 2003.

[25] IETF: NETCONF Working Group.
<url:http://www.ops.ietf.org/netconf/>.

[26] T. Goddard. NETCONF over SOAP. Internet-Draft, feb 2004.
<url:http://www.ietf.org/internet-drafts/draft-ietf-netconf-soap-01.txt>.

[27] Distributed Management Task Force, Inc.
<url:http://www.dmtf.org>.

[28] Common Information Model standards.
<url:http://www.dmtf.org/standards/cim/>.

[29] CIM Managed Object Format (MOF).
`<url:http://www.wbemsolutions.com/tutorials/CIM/cim-mof.html>`.

[30] HP - Web Services Management Framework.
`<url:http://devresource.hp.com/drc/specifications/wsmf/>`.

[31] OASIS Web Services Distributed Management TC.
`<url:http://www.oasis-open.org/committees/wsdm/>`.

[32] R. Neisse, R. L. Vianna, L. Z. Granville, M. J. B. Almeida, and L. M. R. Tarouco. Implementation and Bandwidth Consumption Evaluation of SNMP to Web Services Gateways. *IEEE/IFIP Network Operations & Management Symposium*, April 2004.

[33] Thomas Drevers. Performance of web services based network monitoring. Master's thesis, University of Twente, Enschede, The Netherlands, January 2004.

[34] Information technology – Open Systems Interconnection – Basic Reference Model. ISO/IEC 7498-*.

[35] Marshall T. Rose and K. McCloghrie. Structure and identification of management information for TCP/IP-based internets. RFC 1155, Internet Engineering Task Force, May 1990.

[36] K. McCloghrie and Marshall T. Rose. Management information base for network management of TCP/IP-based internets:MIB-II. RFC 1213, Internet Engineering Task Force, March 1991.

[37] J. D. Case, M. S. Fedor, M. L. Schoffstall, and C. Davin. Simple network management protocol (SNMP). RFC 1157, Internet Engineering Task Force, May 1990.

[38] J. Schönwälder. Simple network management protocol over transmission control protocol transport mapping. RFC 3430, Internet Engineering Task Force, December 2002.

[39] D. Perkins and E. McGinnis. *Understanding SNMP MIBs*. Prentice-Hall, Upper Saddle River, NJ, USA, 1997.

[40] K. McCloghrie and F. Kastenholz. The interfaces group MIB. RFC 2863, Internet Engineering Task Force, June 2000.

[41] Version 2 of the protocol operations for the simple network management protocol (SNMP). RFC 3416, Internet Engineering Task Force, December 2002.

[42] W3C: Web Services Architecture.
`<url:http://www.w3.org/TR/ws-arch/\#whatis>`, August 2003.

[43] W3C: XML Protocol Working Group.
`<url:http://www.w3.org/2000/xp/Group/>`.

[44] R. Fielding, J. Gettys, J. C. Mogul, H. Frystyk, L. Masinter, P. J. Leach, and T. Berners-Lee. Hypertext transfer protocol – HTTP/1.1. RFC 2616, Internet Engineering Task Force, June 1999.

[45] J. B. Postel and J. F. Reynolds. File transfer protocol. RFC 959, Internet Engineering Task Force, October 1985.

[46] Simple mail transfer protocol. RFC 2821, Internet Engineering Task Force, April 2001.

[47] W3C: XML Schema Part 0: Primer.
`<url:http://www.w3.org/TR/xmlschema-0/>`, May 2001.

[48] OASIS Universal Description, Discovery and Integration TC.
`<url:http://www.uddi.org/>`.

[49] XML-RPC Home Page.
`<url:http://www.xmlrpc.com/>`.

[50] OMG: Common Object Request Broker Architecture.
`<url:http://www.corba.org>`.

[51] Sun: Java Remote Method Invocation (Java RMI).
`<url:http://java.sun.com/products/jdk/rmi/>`.

[52] Microsoft: Web Services Development Center.
`<url:http://msdn.microsoft.com/webservices/>`.

[53] IBM: SOA and Web services.
`<url:http://www.ibm.com/developerworks/webservices/>`.

[54] Sun: Java Technology and Web Services.
`<url:http://java.sun.com/webservices/>`.

[55] Novell: Novell exteNd.
`<url:http://www.novell.com/webservices/>`.

[56] BEA: Web services and WebLogic.
`<url:http://dev2dev.bea.com/technologies/webservices/>`.

[57] Web Services Project @ Apache.
`<url:http://ws.apache.org>`.

[58] W3C: Web Services Description Language (WSDL) Version 2.0 Part 1: Core Language.
`<url:http://www.w3.org/TR/wsdl20/>`, March 2004.

[59] OMG: Unified Modelling Language.
`<url:http://www.omg.org/uml/>`.

[60] David Frankel. Using Model-Driven Architecture to Develop Web Services (White Paper).
`<url:http://www.iona.com/archwebservice/WSMDA.pdf>`, April 2002.

[61] OMG: Model-Driven Architecture.
`<url:http://www.omg.org/mda/>`.

[62] Joaquin Miller and Jishnu Mukerji. MDA Guide Version 1.0.1. `<url:http://www.omg.org/cgi-bin/apps/doc?omg/03-06-01.pdf>`, June 2003.

[63] Joaquin Miller and Jishnu Mukerji. Model Driven Architecture (MDA). `<url:http://www.omg.org/cgi-bin/doc?ormsc/2001-07-01>`, July 2001. Document number ormsc/2001-07-01.

[64] Meta-Object Facility (MOF) Specification, version 1.4. `<url:http://www.omg.org/cgi-bin/doc?formal/2002-04-03>`, April 2002.

[65] J. B. Postel. Transmission control protocol. RFC 793, Internet Engineering Task Force, September 1981.

[66] W3C: Web Services Description Language (WSDL) Version 2.0 Part 2: Message Patterns. `<url:http://www.w3.org/TR/wsdl20-patterns>`, March 2004.

[67] Publish/subscribe networking. `<url:http://www.nwfusion.com/details/6165.html>`, May 2003.

[68] Drew Bird. SNMP - Anything But Simple. `<url:http://networking.earthweb.com/netsp/article.php/979991>`, February 2002.

[69] OASIS Web Services Security TC. `<url:http://www.oasis-open.org/committees/wss/>`.

[70] Microsoft: Web Services Security (WS-Security). `<url:http://msdn.microsoft.com/ws/2002/04/Security/>`.

[71] OASIS Security Assertion Markup Language (SAML) v1.1. `<url:http://www.oasis-open.org/committees/download.php/3400/>`.

[72] W3C: XML Signature WG. `<url:http://www.w3.org/Signature/>`.

[73] W3C: XML Encryption WG. `<url:http://www.w3.org/Encryption/>`.

[74] W3C: XML Key Management Specification (XKMS). `<url:http://www.w3.org/TR/xkms/>`, March 2001.

[75] E. Rescorla. HTTP over TLS. RFC 2818, Internet Engineering Task Force, May 2000.

[76] S/MIME version 3 message specification. RFC 2633, Internet Engineering Task Force, June 1999.

[77] W3C Note: Web Service Choreography Interface (WSCI) 1.0. `<url:http://www.w3.org/TR/wsci/>`, August 2002.

[78] OASIS Web Services Business Process Execution Language TC. `<url:http://www.oasis-open.org/committees/wsbpel/>`.

[79] BEA/IBM/Microsoft: Web Services Transaction (WS-Transaction). <url:http://msdn.microsoft.com/ws/2002/08/wstx/>.

[80] Web Services Atomic Transaction (WS-AtomicTransaction). <url:http://msdn.microsoft.com/ws/2003/09/wsat/>.

[81] BEA/IBM/Microsoft: Web Services Coordination (WSCoordination). <url:http://ftpna2.bea.com/pub/downloads/ws-standards-coordination.pdf>.

[82] Standards for Business Process Modeling, Collaboration, and Choreography. <url:http://xml.coverpages.org/bpm.html>.

[83] Mike Champion. Proposed text on reliability in the web services architecture. <url:http://lists.w3.org/Archives/Public/www-ws-arch/2003Jan/0256.html>, January 2003. Personal contribution on W3C WS architecture mailing list.

[84] Web Services Reliability (WS-Reliability) Version 1.0. <url:http://developers.sun.com/sw/platform/technologies/ws-reliability.html>.

[85] OASIS Web Services Reliable Messaging TC. <url:http://www.oasis-open.org/committees/wsrm/>.

[86] K. McCloghrie and F. Kastenholz. The interfaces group MIB using SMIv2. RFC 2233, Internet Engineering Task Force, November 1997.

[87] P. Grillo and S. Waldbusser. Host resources MIB. RFC 2790, Internet Engineering Task Force, March 2000.

[88] Avaya Labs Research - XML based Mgmt Interface. <url:http://www.research.avayalabs.com/user/mazum/Projects/XML/>.

[89] Microsoft: Distributed Systems Patterns. <url:http://msdn.microsoft.com/library/en-us/dnpatterns/html/EspDistributedSystemsPatternsCluster.asp>.

[90] Aiko Pras and Juergen Schönwälder. On the difference between information models and data models. RFC 3444, Internet Engineering Task Force, January 2003.

[91] A. Westerinen, J. Schnizlein, J. Strassner, M. Scherling, B. Quinn, S. Herzog, A. Huynh, and M. Carlson. Terminology for policy-based management. RFC 3198, Internet Engineering Task Force, November 2001.

[92] Aiko Pras. *Network management architectures*. PhD thesis, University of Twente, Enschede, The Netherlands, February 1995.

[93] M. Tamer Özsu and Patrick Valduriez. *Principles of distributed database systems*. Prentice-Hall, Upper Saddle River, NJ 07458, USA, second edition, 1999.

[94] Information technology – Database languages – SQL. ISO/IEC 9075-*:2003, 2003.

[95] Jeffrey D. Ullman and Jennifer Widon. *A first course in database systems.* Prentice-Hall, Upper Saddle River, NJ 07458, USA, 1997.

[96] Roger S. Pressman. *Software Engineering: A Practitioner's Approach.* McGraw-Hill, London, fourth edition, 1997. European Adaptation. Adapted by Darrel Ince.

[97] NMRG Views of an IETF Information Model.
`<url:http://www.ibr.cs.tu-bs.de/projects/nmrg/infomodel/>`.

[98] J. Schönwälder and A. Müller. Reverse engineering internet MIBs.
`<url:http://www.ibr.cs.tu-bs.de/vs/papers/im-2001.pdf>`.

[99] libsmi - A Library to Access SMI MIB Information.
`<url:http://www.ibr.cs.tu-bs.de/projects/libsmi/>`.

[100] Interactive Objects Software: ArcStyler.
`<url:http://www.arcstyler.com>`.

[101] Marshall T. Rose and Keith McCloghrie. *How to Manage Your Network Using SNMP: The Networking Management Practicum.* Prentice-Hall, Englewood Cliffs, NJ 07632, USA, January 1995.

[102] Dia: a drawing program.
`<url:http://www.gnome.org/projects/dia/>`.

[103] The Apache Jakarta Project.
`<url:http://jakarta.apache.org>`.