Trends in Computer Network Modeling Towards the Future Internet

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Abstract

This article provides a taxonomy of current and past network modeling efforts. In all these efforts over the last few years we see a trend towards not only describing the network, but connected devices as well. This is especially current given the many Future Internet projects, which are combining different models, and resources in order to provide complete virtual infrastructures to users.

An important mechanism for managing complexity is the creation of an abstract model, a step which has been undertaken in computer networks too. The fact that more and more devices are network capable, coupled with increasing popularity of the Internet, has made computer networks an important focus area for modeling. The large number of connected devices creates an increasing complexity which must be harnessed to keep the networks functioning.

Over the years many different models for computer networks have been proposed, and used for different purposes. While for some time the community has moved away from the need of full topology exchange, this requirement resurfaced for optical networks. Subsequently, research on topology descriptions has seen a rise in the last few years. Many different models have been created and published, yet there is no publication that shows an overview of the different approaches.

1 Introduction

Communication networks, such as the Internet, play a fundamental role in modern societies and economies. It is nearly superfluous to remind anybody of the many changes that have occurred in the last twenty years since the invention of the World Wide Web and the wide adoption of the TCP/IP protocol suite.

Less known is that the role of networks is becoming even more central in emerging ICT architectures. In these new infrastructures, which are labeled as *Future Internet*, there is a much more integrated operation of networking, computing and storage devices. All these components are being managed and monitored in a coordinated manner in order to deliver services to applications and end users.

One basic rule holds for both the current Internet and the upcoming Future Internet platforms: the design, planning, management and monitoring of the network rely on the knowledge of its topology. A network topology provides in fact information on the location of devices and on the connections between them; this information in turn gives a view of the physical and logical structure of the network. Topologies are expressed as *network models*, and we use these two terms interchangeably in this article.

Topology information needs to be available to all devices within the network to operate properly, to external tools that act on the network and to applications that use the network. We see three main challenges for network models.

- *Handling different abstraction levels:* From a devices perspective there is a wide range of topology details needed: at the edges of the network knowledge can be as minimal as knowing where the next hop is, while within the core devices require much more information.

- *Managing multi-domain communication and path setup:* External tools that operate on the network need to be aware of the network or to provide metadata of the network; monitoring tools require a comprehensive model to describe all relevant details of computer networks and the connections through them, while bandwidth-on-demand tools used in circuit switched networks will only need to exchange some detail of network topology to be able to efficiently plan connections.

- *Integration with computing-network-storage-planning services:* Once applications become more dependent on performance of the computer network they need more detailed models to be able to express their requirements, and closely monitor network performance.

In this article we provide an overview of some of the most used and well known network models. It is our intention to guide the reader through a historical journey that ultimately clarifies the need for new modeling approaches to support the Future Internet. To this end we first look at network descriptions in the history of the Internet in section 2. We then provide a categorisation of network models (section 3).

Following our model categorisation we present management models (section 4), monitoring models (section 5) and generic models (section 6). We also introduce the existing Future Internet model (section 7). Section 8 provides an overview and discussion on the current state of network models research. We conclude the article with a summary and the upcoming research challenges in section 9.

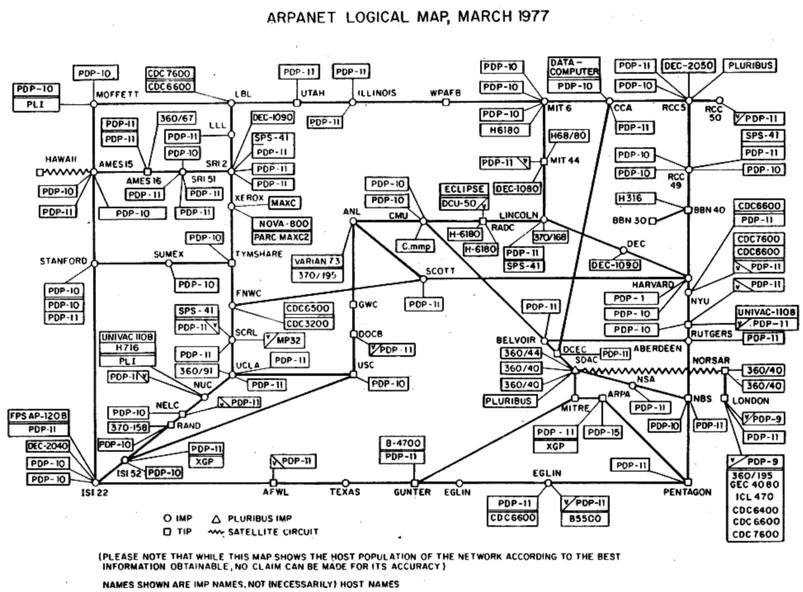

Figure 1: ARPANET logical map, March 1977, an example of early network models

2 Historical Role of Network Descriptions

Before delving into current network modelling efforts that aim to support the Future Internet, it is helpful to understand the role and evolution that network descriptions have had in the past years.

We will show that networks have evolved from the original packet-switched architectures, to use optical circuit-switched designs to finally converge towards the Future Internet hybrid models, i.e. networks offering both packet and circuit switching services. We will also show that during this evolution there is one constant requirement that has not changed: the need to exchange information about the network topology. For packet-switched networks topology information is needed for the operation of routing protocols, for circuit-switched and hybrid networks it is required for the creation of dedicated connections among end-points.

Packet-switched networks

Topology descriptions have been used to support computer networking activities since the start of the Internet. The most commonly used technique to capture a network topology is of course a graphical representation. One of the obvious drawback of this method is that it does not scale well as the network becomes larger, making automated tools necessary. Fig. 1 shows an early representation of the ARPANET[62]. This network started out with just four nodes in 1969, but quickly grew larger. The figure shows a large network with many devices and connections which is hard for humans to grasp in its entirety.

The ARPANET originally used Interface Message Processors (IMPs) to route messages through the network[44]. These IMPs performed regular delay measurements to all destinations, and then broadcasted the result. These results were combined and then stored to function as a sort of distance-vector protocol. Over the years the routing between IMPs was gradually improved, until in 1983 the ARPANET switched over to TCP/IP.

Research on TCP/IP had already been going on during the seventies on several test networks[26]. During this time the Routing Information Protoocol[45] was also developed, implementing a distance-vector protocol. Distance-vector protocols form an abstract view of the network, using the distance and general direction as a way to select the forwarding interface. Similar to this is the path-vector Border Gateway Protocol [53, 58] which rely on operator defined paths in the network, serving most backbone networks in the Internet. These protocols no longer need a complete picture of the network. Instead, each router has a (different) aggregated view of the network, gathered from exchanging aggregated information with others.

During the late 70s and early 80s several different link-state routing protocols were developed, among them IS-IS and OSPF[57, 59]. Link-state routing protocols broadcast messages containing the states of links, and where they directly connect to. Traditionally this broadcasting is limited to smaller areas, and not the whole network. Within an area, all routers do form a complete view of the topology, and use this to calculate the shortest path tree. Link-state networks are mostly used in local networks.

When relying on distance vector protocols full topology distribution is no longer a requirement. However, having a full network description available is still needed by link-state protocols and it can in general still be helpful in monitoring or problem detection. In both cases the transfer of information regarding the topology is done directly by the network nodes.

Circuit-switched and hybrid networks

The methods to derive knowledge on the network topology we just described have been driven by the routing protocols, and as such they are only applicable to packet-switched networks. They are not very useful in the context of circuit-switched or hybrid networks. Models better suited for these latter situations have emerged in the past years.

For circuit-switched networks full topology distribution is still required. In order to send data from a source to a destination in a circuit-switched network, a circuit must be configured. In telephony networks dynamic provisioning is achieved by using strict addressing, aggregated static routes, and large capacity[46]. For circuits in data networks this is not feasible, since there is no strict numbering plan, and the overall capacity compared to the circuits is not that great.

Asynchronous Transfer Mode tried to merge the world of circuit-switched networking with packet-switched networking. There the Private Network-to-Network Interface [60] was used to relay topology information, and also included some ideas on topology aggregations. In the end, ATM never became very widely adopted, and is not currently in mainstream use.

GMPLS with its Path Computation Element[28] takes a different approach for inter-domain path computation. Instead of sharing topology information, every request in the network is broadcast to peers. The route of the request is recorded and replied along the same path to implement a circuit reservation request. While technically feasible, this approach poses problems as the number of requests goes up. While GMPLS is implemted intra-domain, we have not seen inter-domain deployments.

A different approach is seen in hybrid networking[29]. Many research and educational networks are currently offering circuits on their own network, and recently also started experimenting with inter-domain circuits[61]. Here the topology of a domain needs to be exported in full or in an abstracted way to the neighboring domains. The representation of the network needs to be consistent and agreed upon, such that inter-domain circuit provisioning tools can take decisions on how to engineer a circuit.

While the ARPANET and Internet have moved away from the need of full topology exchange, the need for topology description and exchange has risen again for optical networks. Subsequently, research on topology descriptions has also seen a rise in the last few years. Many different models have been created and published, yet there is no publication that shows an overview of the different approaches.

3 Topology Categories

The historical perspective we just gave provides a sense of why models are needed, and how they have been used concretely. But it is also useful to categorise the various models in a more general way. We can, in fact, analyse and compare different computing models suitable for Future Internet infrastructures based on the following three features:

1. their purpose from an application perspective,
2. the range of infrastructure layers covered by the models,
3. the functional scope covered by the models.

An overview of these features and how they relate to each other is shown in Figure 2, where we provide two main blocks, i.e application and future internet infrastructures, and we position models in them according to their characteristics.

From an application perspective, we distinguish between three different models in terms of the type of application they support.

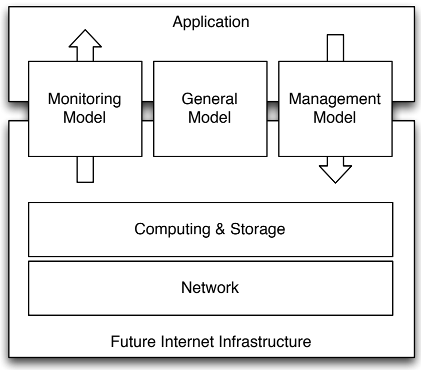

Figure 2: Computing Infrastructure Models

- *Management* models are used in network-management applications or to restrict actions that can be taken on a network.
- *Monitoring* models are used for external applications to describe the dynamic aspects of a computing infrastructure.
- *General* infrastructure models are used for applications that require a static view of computing infrastructures.

When starting from the infrastructure perspective, different models cover a different range of layers in the infrastructure. In this paper we distinguish between models that focus on a single technology layer of the infrastructure and models that cover multiple layers of technology. We also identify two different functional aspects of a Future Internet infrastructure that can be covered by a model. Most of the models discussed are focused on the network infrastructure that connects the different resources in the computing infrastructure while other models also include computing and storage capabilities of the Future Internet infrastructure.

Besides the content, we will also take the modeling approach into account for comparing and analyzing different models. For this purpose we identify the following types:

1. byte format, used in communication protocols and aimed at compact descriptions;
2. database schema, used to describe the content of the database in which the instances of the infrastructure are stored;
3. Unified Modeling Language, used to describe the classes and relations in an object oriented model;

4. Extensible Markup Language (XML), used to provide a schema for the model and syntax that is application and programming language independent;

5. Semantic-Web based models, i.e. models based on the Resource Description Framework or the Web Ontology Language, used to provide semantic models of future internet infrastructures.

Table 1: Overview of model characteristics.

Model	Main Purpose	Scope	Type	Standard O
SNMP	Management	Network	DB schema	IETF
NetConf	Management	Network	XML	IETF
OSPF(-TE)/GMPLS	Management	Network	byte format	IETF
CIM	Management	Network + Comp & Storage	UML + XML	DMTF
DEN-ng	Management	Network + Comp & Storage	UML	DMTF
perfSONAR/NMC	Monitoring	Network	XML	OGF
cNIS	Monitoring	Network	DB schema	-
MOMENT	Monitoring	Network + Comp. & Storage	OWL	-
G.805/G.809/G.800	General	Network	None	ITU
NDL	General	Network	RDF	-
NML	General	Network	XML + OWL	OGF
RSpec	Request	Comp & Network	XML	-
VxDL	Request	Comp & Network	XML	-
NDL-OWL	General	Network + Comp & Storage	OWL	-
NOVI/GEYSERS/INDL	General	Network + Comp & Storage	OWL	-

In Table 1 we provide an overview of the models and their main characteristics discussed in the following sections.

4 Management Models

Network management has used several different information models over the years, and newer models are being proposed. These models are mainly used for management of devices, or in protocols to exchange necessary topology information. They are generally aimed at specific applications, the information expressed in the protocols is not meant to be generically available nor extensible.

4.1 SNMP

The Simple Network Management Protocol[1][25, 71] is a set of standards describing a protocol, a database schema, and data objects. The whole suite was

[1]Technically, the information model is formed by the MIBs, Management Information Bases, and SNMP denotes the whole set: protocol, information and data model.

originally created as a way of both monitoring and managing network resources. In current networks it is mainly used for monitoring purposes.

Diagnostic, performance and configuration information of network devices can be retrieved from the Management Information Base (MIB) of devices using Simple Network Management Protocol (SNMP) messages. The MIB is a tree of name – value pairs, which can be requested and changed. The values are restricted to three different types of datatypes: integer, string and sequence of datatypes. A large part of the MIB tree is standardised, but vendors also have their own private part of the tree. This vendor space is used to store most configuration and performance data of their devices in a proprietary format. Virtually all networking devices support SNMP, with different levels of detail in their MIB.

The network description provided by SNMP is distributed over the devices. Depending on the layer the device is operating on, it may have a pointer (address or identifier) to its neighbours on that layer. A view of the whole topology can be created by combining the information gathered from all the devices.

4.2 NetConf

The Internet Engineering Task Force has recently worked to replace SNMP with a new standard, NetConf[34][35]. While SNMP uses its own protocol and only allows for three data-types, NetConf uses XML, allowing for many more data-types. NetConf defines a way of transporting monitoring data and change requests over a small set of existing protocols. NetConf is aimed at distributing diagnostic, performance and configuration information, but also for managing devices. NetConf is currently being introduced in networking devices.

As NetConf follows similar principles as its predecessor, the network description provided by NetConf is similarly distributed over the managed devices. Each device will have information about the neighbour it connects to on the layer it operates on. The network topology can be created by combining the information of the devices in the network.

4.3 GMPLS

GMPLS, Generalized Multi-Protocol Label Switching[54][38], is a protocol suite developed by the IETF for the provisioning and management of label-switched paths through multi-technology networks. It provides a unified control and management plane for the management of multi-layer networks. Networking devices use the Open Shortest Path First - Traffic Engineering (OSPF-TE) protocol to exchange topology data with their neighbours. Devices broadcast the received topology data to their other neighbours, so that in the end all the devices in the domain have the same view of the network topology.

The topology data in OSPF-TE is exchanged in Link State Announcements packets inside network domains. The topology data contained therein is encoded in a compact byte format, using specifically defined header fields and Type-Length-Value containers. This format is designed to be easy to process and store for participating network devices, but it is hard to export to external applications. The message format is somewhat extensible, there is specific room for other applications to add data to the messages. The data must fit in the Type-Length-Value container, and can be processed by agents participating or listening to the OSPF-TE process.

Since OSPF-TE is only used intra-domain, there is no inter-domain exchange of messages or information. In order to allow for inter-domain provisioning, the Path Computation Element architecture [37] has been defined. Generalized Multi-Protocol Label Switching (GMPLS) operators have expressed a desire to keep network topology data confidential, so the path computation architecture works by broadcasting requests, rather than by distributing topology information[28][23].

4.4 CIM and DEN-ng

The Common Information Model (CIM)[33] is a network device information model commonly used in enterprise settings. CIM is developed by the Distributed Management Task Force[1] and it is an object-oriented information model described using the Unified Modeling Language. This information model captures descriptions of computer systems, operating systems, networks and other related diagnostic information. CIM is a very broad and complex model, the current UML schemata of the network model span over 40 pages, the total model is over 200 pages.

A mapping from CIM to XML is also defined, which is mainly used in Web-Based Enterprise Management. This is mainly implemented in enterprise-oriented computing equipment, and operating systems such as Windows and Solaris. The CIM model is highly expressive, and is still actively developped. There have been many significant changes in the infrastructure part of CIM over the past two years, both introducing new elements, as well as deprecating or changing existing elements. The CIM model is capable of capturing the complete physical setup, and almost everything with regards to the configuration of devices. The model is capable of capturing the information with a very high level of detail, yet provides almost no abstraction layer above this, making it very hard to reason generically using this model.

A successor to CIM is the Directory Enabled Networking - next generation (DEN-ng) model, Directory Enabled Networking – next generation[63], which extends the CIM model also with description of business rules. The idea behind the model is that with the right software, the business rules combined with the capabilities of the devices can be automatically transformed into configurations of firewalls, user restrictions, et cetera. This requires that all configuration management is managed centrally, or at least by the same tools.

5 Monitoring Models

The previous section provided an overview of management models, which are usually aimed at specific tools for network and device management. Many communities like to provide more generic access to monitoring data, so monitoring models have been created. These models can take output from different tools and combine them into a single model.

5.1 perfSONAR / NM and NMC

An early model for network topology description is the perfSONAR[22][43] model. perfSONAR is a network monitoring architecture. It stores data from different measurement tools which are then made available publicly. This is particularly intended for inter-domain network connection debugging[70].

The perfSONAR architecture has been implemented by different partners, providing two different, compatible implementations. The model has later been brought to the Open Grid Forum (then Global Grid Forum)[7] for standardisation. This resulted in the Network Measurements Working Group (NM-WG)[6] which produced a standardised schema in 2009[3].

The NM-WG schema contains a base schema to describe network measurement tools, and their results. There is also a time schema to accurately describe time values in these measurements. Of particular interest here is the topology schema, which provides a basic representation of network topologies using hierarchical constructs in XML. This schema allows for a simple description of domains, nodes, ports and their connections.

This schema is also used in the Inter-Domain Controller Protocol[30], which is currently in use in many circuit provisioning tools, e.g. OSCARS[42]. The OSCARS tool allows users to make circuit requests for the Energy Sciences Network (ESnet[18]), and has also been implemented on the Internet2 ION network[14].

The Network Measurement and Control WG has currently taken over the activities of the activities of the NM-WG and is continuing development of the measurements schema. The topology schema development has moved to the Network Markup Language, which we discuss later.

5.2 cNIS and AutoBAHN

cNIS is the network topology description format for GÉANT network[19] and is used as basis for the AutoBAHN[20] bandwidth on demand system. The data model is implemented in a database schema[11]. This schema includes fixed descriptions of a set of layers used in the GÉANT network, such as Ethernet, and MPLS.

The AutoBAHN bandwidth on demand system at first started with the cNIS, but later extended it towards their own model[24]. The AutoBAHN system uses a Domain Manager which maintains the local topology. This Domain Manager does automatic topology aggregation before exporting a topology to the Inter-Domain Manager. Interestingly, the Inter-Domain Manager uses extensible OSPF messages to exchange inter-domain topology information.

The Stitching Framework[36] is also a GÉANT activity, and it describes a framework for 'stitching' together different technologies in bandwidth-on-demand systems in a multi-domain and multi-layer environment. It provides a framework to define the required information for creating connections across multi-domain multi-layer networks. The Stitching Framework has been integrated into the latest version of cNIS where it can stitch together the technologies defined there. It should be noted that the Stitching Framework is built generically, and could also be applied to other more expressive models.

5.3 Monitoring and Measurement Ontology

The perfSONAR and NM-WG work served as an important inspiration for the Monitoring and Measurement Ontology (MOMENT) developed by ELTE[55]. This ontology has taken the initial concepts from NM-WG and implemented them into an Web Ontology Language (OWL)-based ontology. This ontology is mostly aimed at measurement tools and results, which using their OWL ontology, can both be expressed in great detail.

The ontology allows an application to describe the exact circumstances of a measurement. For example that a `traceroute` command was performed at a certain time, the parameters of that command, a description of the network at that time, and the results of the command itself. These kinds of measurements can then be recorded in a database, where they can be easily correlated and analyzed using the generic description of the data.

The MOMENT ontology has served as a way of describing data for the ETOMIC[56] infrastructure. This infrastructure consists of several nodes together forming a network measurement virtual observatory. The OWL-based ontology then makes it possible to easily share and reuse measurement data with others.

The experiences of the MOMENT ontology have been used also in the development of the NOVI monitoring ontology.

6 General Models

In the previous sections described management and monitoring models, which are aimed at management and monitoring applications respectively. Another category is the set of general models, which aim to provide a more general description of the network topology so that other applications can use them.

6.1 G.805, G.809 and G.800

A very generic set of models are the network models defined by the International Telecommunication Union (ITU). These models are theoretical models, in the sense that they have no explicit data model defined for them. However they are important to discuss here as they have identified and defined important terminology for network topology description, especially concerning multi-layer networks.

In 2000 the ITU published the G.805 network model[47]. This model allows the description of all kinds of transport networks, and especially different layers and adaptations in that network. It is a very comprehensive, but also complex model. A more readable introduction is available[31]. The G.805 model allows the modelling of circuit-switched networks, and in 2003 the model was extended in G.809[48] to also model connection-less networks. Then in 2007 these models were combined, along with some others into G.800: 'Unified functional architecture of transport networks'[49].

These models are very extensive and generic, allowing to describe any kind of existing network, but also future network technologies. The models have identified some fundamental concepts, such as:

- *Layers* is defined as the set of connection points of the same technology,
- *Adaptations* are the functions performed on data to transform it from one layer to another,
- *Labels* identify different flows of data in a Layer.

So as a simple example, VLAN tagged traffic is a specific Layer, the adding of a VLAN tag to a packet is an Adaptation, and the VLAN tag is used to identify a data flow among the other traffic.

However, G.805, G.809 and G.800 are only graphical models, there is no data model underlying these information models, making them hard to use in practice. The models do provide a very fundamental theoretical groundwork, which is why NDL and NML have taken it as a source of inspiration.

6.2 Network Description Language

In 2006 the University of Amsterdam published a method of using RDF to describe networks[66], called the Network Description Language (NDL). This uses a simple model to describe devices, interfaces and their connections. The descriptions would then be available to applications in a standard format. The initial idea was also to apply the distributed description capability of the semantic web, similar to the Friend of a Friend network[4]. This allows networks to independently describe their network topologies and link them together so that they together form a global description of the network.

The initial model of NDL (v1) was simple, and in some ways similar to the model used by PerfSonar, but implemented in Resource Description Framework (RDF). Using ideas from G.805 we extended NDL to version 2, which describes multi-layer networks generically[32][65]. This model introduces a notation for the G.805 concepts of Layers, Adaptations and Labels. This allows for descriptions of any kind of network topology, ranging from physical networks to completely virtualised networks, and also the relations between those network layers.

NDL has been used as one of the models on which the Network Markup Language is based, and also heavily influenced the design of the NOVI and GEYSERS information models.

6.3 Network Markup Language

During 2007 efforts have been combined from PerfSonar, NM-WG and NDL to create a standard network topology information model. A new working-group was formed at the OGF called the Network Markup Language[2]. This group aims to create a generic network model that can be used for describing measurements, monitoring, describing topologies, and also requests.

The Network Markup Language (NML) schema describes networks using uni-directional constructs. The unidirectional Port objects can be connected together, externally through Links or internally through a Node's Crossconnect. The model also includes the capability of describing multi-layer networks based on the ideas from G.805 and NDL as described earlier. The unidirectional model causes the network model to be very verbose, however this allows the model to be more generic, as a unidirectional model can describe bidirectional networks, but vice versa this is not possible.

The standardisation process has recently resulted in the publication of the first NML base schema[67]. To support different applications, NML has two different data models, one in XML and one in OWL.

7 Future Internet Models

In recent years several initiatives have started to work on so-called Future Internet platforms. Examples are the GENI[12] initiative in the United States, and the FIRE[5] initiative in the Europe. From these several different projects have started, which we discuss below.

7.0.1 RSpec & RSpec v2

The GENI project[12] in the United States has been working on very large distributed virtualization infrastructures, such as PlanetLab[27, 16], and ProtoGENI[17]. These testbeds contain nodes distributed over different locations, connected to the Internet, where users can request virtual machines and conduct network experiments.

Initially PlanetLab developed the Slice-based Federated Architecture (SFA) format to provide infrastructure and request descriptions. The first version of this format have been defined in Resource Specification (RSpec)[9]. This later evolved into ProtoGENI RSpec v2[10], which has been chosen as the standard interchange format for PlanetLab, and all other Global Environment for Network Innovations (GENI) platforms.

The RSpec v2 format is a simple XML based format geared towards the specific use in virtual environments. It allows platforms and users to describe nodes, their virtualisation properties, and a very limited form of network connectivity. The format works very well with PlanetLab and compatible systems, but it is very hard to use when describing any other kind of network or infrastructure.

7.0.2 Virtual private eXecution infrastructure Description Language

The Virtual private Execution infrastructure Description Language (VxDL) has been developed by INRIA and Lyatiss[50, 15]. VxDL uses an XML syntax to express infrastructure requests in varying levels of detail. Such a request consists of four parts: a general description, a description of non-network resources, a network topology, and the time interval for this reservation.

VxDL is used in GRID5000[13], the GEYSERS project (see section 7.2, as well as a commercial product developed by Lyatiss.

7.1 Network Description Language OWL

RENCI[8], a GENI participant, has also built an infrastructure, called ORCA-BEN[21, 69]. This infrastructure contains several locations with virtualisation capabilities, and a completely controllable optical network. In order to control and manage this they have extended NDLv2 to the OWL syntax, creating Network Description Language OWL (NDL-OWL). This also extends NDL with more virtualisation and service description features to describe their infrastructure. These descriptions are then used in the client software to describe requests, but also in the management software to match the requests with the available infrastructure.

The development of NDL-OWL and ORCA-BEN has been performed in the context of the GENI project, which means that ORCA-BEN is able to communicate with other GENI platforms, including platforms speaking RSpec v2. NDL-OWL is thus a superset of RSpec v2.

7.2 NOVI, GEYSERS and INDL

The NOVI project aims to federate Future Internet platforms and one of the challenges of the NOVI Information Model is to interact with different platforms[68, 64]. Using NML in the information model provides the basis for interaction between NOVI and the FEDERICA and PlanetLab platforms. Not only does the information model have to map to concepts used in these platforms, it also needs to be able to accommodate interaction with other platforms that may be added to the federation in the future. By adding concepts from the MOMENT ontology also to the NOVI ontologies, users can easily use monitoring tools and data to get a comprehensive view of their requested infrastructure. The NOVI ontology suite allows a complete semantic description of a Future Internet federation. NOVI has ontologies for the infrastructure, but also for monitoring tools and results, as well as policy aspects and rules. Of special interest in the

NOVI model is the *unit* ontology, which generically describes the units used for capacity, measurements, et cetera.

One of the key innovations of GEYSERS is to enable virtualisation of optical infrastructures. The GEYSERS Information Modeling Framework (IMF), is currently under development to provide an information model for the Logical Infrastructure Composition Layer [39]. This layer is the element responsible of managing physical resource virtualisation and composing Virtual Infrastructures. These are then offered as a service within the GEYSERS architecture.

The information models in both NOVI and GEYSERS are used to both describe the infrastructure and also to allow users to express requests. Once an infrastructure request is handled by either system, the result is also described in the same information model and made available to the user. This description can then also be used to correlate data from the active monitoring tools.

These platforms show that infrastructure provisioning is a complex interplay of different hardware and software tools, which benefits greatly from having an interoperable semantic model to exchange information. These models combine many aspects of the previous models, providing users with a single semantically compatible model for describing requests, physical and virtual infrastructure, as well as directly related monitoring information.

The Infrastructure and Network Description Language (INDL)[40, 41] is an evolution of the Network Description Language, combined with the experiences in NOVI and GEYSERS. We have taken the general model from NML, and added capabilities to describe the virtualisation of nodes and infrastructure. The model is actually not that different from the model in NOVI and GEYSERS, but provides a more reusable model available for other Future Internet platforms.

8 Discussion

This article presented an overview of the current state-of-the-art of network description models, with the goal to show how these models are suitable to the needs of Future Internet platforms. Figure 3 shows an overview of the described information models and how they have influenced each other. This figure groups the models by intended usage: at the top of the figure we have the models more related to management; we then show the monitoring models, and below them the general models. The Future Internet models which combine the ideas of the monitoring and general models to form a complete ontology for future infrastructures are on the bottom and right side of the figure.

The information models described in section 4 are aimed at describing purely functional topology and diagnostic information, making these management models. For example the GMPLS information model is aimed switches and routers. The data model is designed for compactness and is therefore not easy for other applications to understand, nor is it human readable. CIM and DEN-ng are also management models, albeit at a higher level, combining all the information of different low-level management models. This creates an aggregated management model at the enterprise level. The information models in these categories are

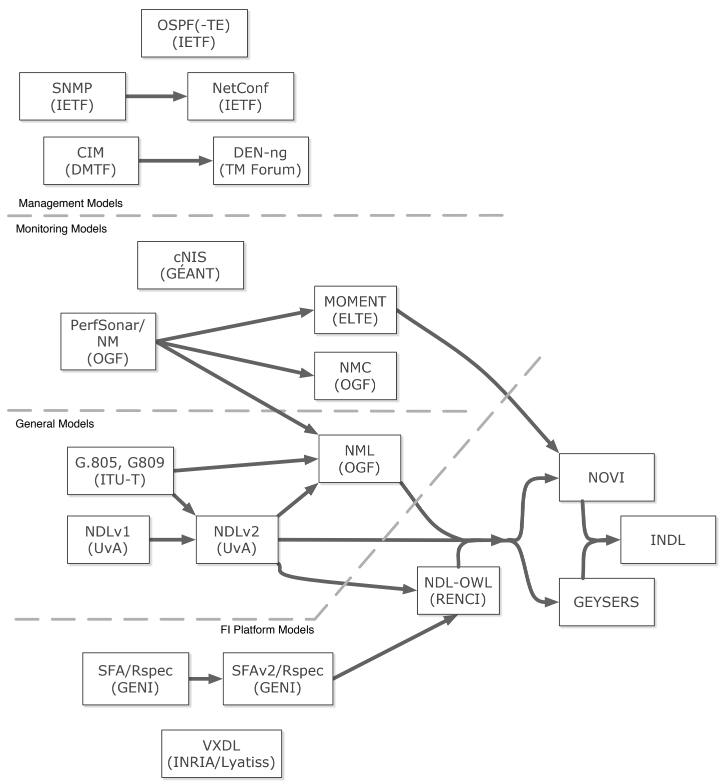

Figure 3: An overview of different information models

both aimed at management, informing the direct operators of those machines. These management models are aimed specifically at a single task, which they perform very well. The models are used in isolated contexts and domains, and the models are not generic enough to be used in applications not specifically aimed at these contexts. Most of the other information models described in this article have some form of an XML data model and are thus more generally usable.

The monitoring models, PerfSonar/NM-WG, cNIS and MOMENT, have been defined specifically to capture data from many different tools, and store and share them in a generic way. These monitoring models are targeted at capturing monitoring information, network measurement data along with topology data of those measurements. Unlike the management models, the measurement models aim to make the data as portable as possible so that different tools and applications can interpret the data, instead of a single management application. The network topology description elements of these models support the description of results, and are not that advanced in describing different technologies, or the dynamics between the technologies.

The general models are aimed specifically at describing network topologies. The initial model of NDL was also not capable of describing multi-layer networks, but this changed due the influence of the ITU G.805, G.809 and G.800 models. The ITU models have very clearly identified and extensively defined a terminology for multi-layer networks. Using the generic (de)adaptation and labelling concepts it becomes possible to describe any kind of technology, without being dependent on a predefined notation for that technology. The NDL, and NML models aim at generic network descriptions that can be extended or embedded in other models. The intention of the generic models is to provide applications using the data enough information to act on the network, either by provisioning circuits or by adapting the applications behavior to the capabilities of the network.

The general models have been very influential in the creation of most models of the Future Internet. The initial models, SFA and VxDL, created for the Future Internet have been limited models to allow users to easily describe their requests for virtual infrastructures. The later Future Internet models, NDL-OWL, NOVI, GEYSERS and INDL, have built on both these simpler request-like models, as well as the general models to support the management of the Future Internet testbeds. This support is both for users in clearly defining their requests and the resulting topology. But the model also supports the management of the testbed to describe in a single model the physical resources, as well as the reserved virtual infrastructures.

The semantic web nature of the general models allow them to be easily incorporated in other models. Which is what we see happening somewhat in the NDL-OWL model, but even more so in the NOVI and GEYSERS models. The have taken the basic network models of NDL/NDL-OWL/NML and extended these ideas towards virtual infrastructures and also adapted the request models to form a single information model for Future Internet infrastructures. The NOVI model takes this another step further by also integrating the MOMENT monitoring and measurement ontology, forming a complete semantic network model.

9 Conclusion

Our article documents a clear evolution in the modeling of networks and infrastructure toward supporting Future Internet operations.

On one hand we have shown that management models have changed less, given they are all aimed at specific applications, and target very specific use-cases or tools. The hardware or chosen management software limits the choice for an information model in this case.

On the other hand, monitoring, general, and Future Internet models have all evolved significantly. The evolution we have documented shows that from several different initiatives at first, there has been a convergence on the newly defined Network Markup Language standard. Many of the models were of direct influence to NML, so the standard is suitable for use in monitoring, provisioning as well as request modelling. The Future Internet models we are interested in have taken NML as their base model and extended it where necessary to describe resources beyond the network topologies. These extensions are also again converging in an extended model, INDL.

9.1 Challenges for Network Models

Computer networks have become complex systems over the years and interactions with the network, especially circuit switched networks, should not be taken for granted. Our overview of the different models we presented demonstrates that creating an information model for computer networks is not a simple feat. This is even more true for Future Internet platforms: there, networking is becoming more and more ubiquitous and more integrated in the computing-storage fabric, making the management of computer networks a much more difficult task.

We have identified three challenging areas for network models in the coming years:

- handling abstraction levels appropriately;
- managing multi-domain communication and path setups;
- integration with computing-networking-storage planning services.

In 35 years we have moved from a situation where the entire Internet could be captured in a single figure (see Figure 1) to a situation where we are running out of IPv4 address, with many more devices hidden behind NAT solutions. Network management has no choice but to move with this pace, requiring higher abstraction levels. Network information models are a necessary prerequisite for creating these abstraction levels. Current models do not adequately handle different abstraction levels in the same models.

Network descriptions are important in supporting path selection tools. Consider the architecture described by Lehman et al.[52] which points to the fact that an interoperable inter-domain topology description is necessary in order to allow path selection for multi-domain multi-layer circuit-based networking. Path selection in single layer networks is trivial, however in multi-layer networks it is much harder, and often NP-complete[51]. The generic way of describing network technologies enabled by the abstract models of G.805 and G.809 makes it possible to create generic path selection algorithms which will be able to handle many if not all existing and future network technologies. The way that network topologies are represented are an important factor in supporting the path selection process.

The problem of multi-layer path selection has many similarities with matching requests with (virtual) infrastructures. The nodes and services that are part of the request can be seen as special kinds of links connected to the network, similar to multi-layer network requests. By using generic models the application can choose to solve this problem directly, or it can choose to carve the problem up and delegate subproblems to the relevant planning services. This will lead the way towards a complete Future Internet infrastructure.

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List of Abbreviations

BGP Border Gateway Protocol

CIM Common Information Model

DEN-ng Directory Enabled Networking - next generation

DMTF Distributed Management Task Force

FIRE Future Internet Research and Experimentation

GENI Global Environment for Network Innovations

GEYSERS Generalized Architecture for Dynamic Infrastructure ServicesAn FP7 EU Project

GLIF Global Lambda Integrated Facility

GMPLS Generalized Multi-Protocol Label Switching

IEEE Institute of Electrical and Electronics Engineers

IETF Internet Engineering Task Force

IS-IS Intermediate System to Intermediate System

ITU-T Telecommunication Standardization Sector (coordinates standards on behalf of the ITU)

ITU International Telecommunication Union

MIB Management Information Base

MOMENT Monitoring and Measurement Ontology

NDL-OWL Network Description Language OWL

NDL Network Description Language

NM-WG Network Measurements Working Group

NMC Network Measurement and Control WG

NML Network Markup Language

NOVI Networking Over Virtualised InfrastructuresAn FP7 EU Project

OGF Open Grid Forum

OSPF-TE Open Shortest Path First - Traffic Engineering (An extension of OSPF)

OSPF Open Shortest Path First

OWL Web Ontology Language

PNNI Private Network-to-Network Interface

RDF Resource Description Framework

RFC Request For Comments (an Internet Engineering Task Force (IETF) memorandum on Internet systems and standards)

RIP Routing Information Protoocol

RSpec Resource Specification

SFA Slice-based Federated Architecture

SNMP Simple Network Management Protocol

VxDL Virtual private Execution infrastructure Description Language

INDL Infrastructure and Network Description Language

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