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Towards Automated Network Configuration Management

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Towards Automated Network Configuration Management

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Abstract

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Modern networks are designed to satisfy a wide variety of competing goals related to network operation requirements such as reachability, security, performance, reliability and availability. These high level goals are realized through a complex chain of low level configuration commands performed on network devices.

As networks become larger, more complex and more heterogeneous, human errors become the most significant threat to network operation and the main cause of network outage. In addition, the gap between high-level requirements and low-level configuration data is continuously increasing and difficult to close. Although many solutions have been introduced to reduce the complexity of configuration management, network changes, in most cases, are still manually performed via low–level command line interfaces (CLIs). The Internet Engineering Task Force (IETF) has introduced NETwork CONFiguration (NETCONF) protocol along with its associated data–modeling language, YANG, that significantly reduce network configuration complexity. However, NETCONF is limited to the interaction between managers and agents, and it has weak support for compliance to high-level management functionalities.

We design and develop a network configuration management system called AutoConf that addresses the aforementioned problems. AutoConf is a distributed system that manages, validates, and automates the configuration of IP networks. We propose a new framework to augment NETCONF/YANG framework. This framework includes a Configuration Semantic Model

(CSM), which provides a formal representation of domain knowledge needed to deploy a successful management system. Along with CSM, we develop a domain–specific language called Structured Configuration language to specify configuration tasks as well as high–level requirements. CSM/SCL together with NETCONF/YANG makes a powerful management system that supports network–wide configuration. AutoConf supports two levels of verifications: consistency verification and behavioral verification. We apply a set of logical formalizations to verifying the consistency and dependency of configuration parameters. In behavioral verification, we present a set of formal models and algorithms based on Binary Decision Diagram (BDD) to capture the behaviors of forwarding control lists that are deployed in firewalls, routers, and NAT devices. We also adopt an enhanced version of Dyna-Q algorithm to support dynamic adaptation of network configuration in response to changes occurred during network operation. This adaptation approach maintains a coherent relationship between high level requirements and low level device configuration.

We evaluate AutoConf by running several configuration scenarios such as interface configuration, RIP configuration, OSPF configuration and MPLS configuration. We also evaluate AutoConf by running several simulation models to demonstrate the effectiveness and the scalability of handling large-scale networks.

This dissertation is lovingly dedicated to my family

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Chapter 1

Introduction

The aim of network management is to provide to network-based services and applications a networked system with the desired level of quality and availability, and to provide a mechanism for a rapid, flexible deployment of networked resources. Hegering [37] describes management of networked systems as a collection of all measures necessary to ensure the effective and efficient operation of a system and its resources pursuant to corporate goals. The Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T) defines management as a set of capabilities to allow for the exchange and processing of management information to assist Public Telecommunication Operators (PTOs) in conducting their business efficiently [48]. Therefore, network management is any activity (planning, configuration, monitoring, etc) that ensures the proper operation of a network that satisfies certain high–level requirements such as business, performance, security, connectivity and availability.

The International Organization for Standardizations (ISO) has divided management activities into five functional areas: Fault, Configuration, Accounting, Performance and Security [44]. Fault management concerns on monitoring devices activities, detecting faults, and performing root-cause analysis to isolate and correct the abnormal conditions. Configuration management concerns with the ability to access configuration data in order to add new

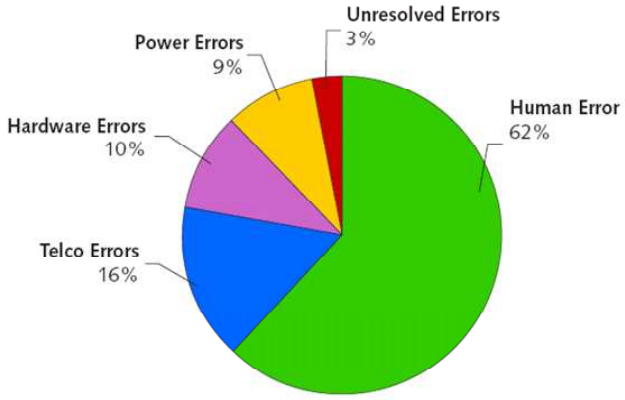
configuration, delete an existing configuration, or update a configuration data. Accounting management concerns on billing and accounting issues related to the use of network resources. Performance management concerns on assessing and evaluating network performance. Security management concerns with the ability to provide security assurance and protection.

Unlike other functional areas of network management, where read-only operations are performed on network devices to collect operational information, configuration management makes adjustment to the configuration data in order to enable (or disable) network services. In fact, network cannot operate without initially be configured; if network devices are not properly configured, there is no network! Furthermore, all other management functions rely on configuration management to accomplish the desired output. For examples, fault management requires reconfiguration to fix the problems, performance management requires reconfiguration to optimize the network operation, and security management requires reconfiguration to resolve any security violation. Consequently, configuration management is considered the most important management function among other functional areas.

The remaining of this chapter is organized as follows. We first discuss the motivation of our dissertation. Then, we state the problem statement of our research work. Next, we describe the scope of this dissertation and limitations. The following section then lists our contributions. We conclude this chapter with a brief summary on how this dissertation is organized.

1.1 Motivation

Network Configuration management is a complicated task. This is because of the immense complexity and diversity of the underlying network devices such as switches, routers, firewalls, IPSECs, VPN access points, etc. Moreover, many enterprises and service providers are supporting different services and configurations that put network administrators in a very



Source: The Yankee Group 2002 Network Downtime Survey

Figure 1.1: Network Operator errors are the major cause of network downtime

difficult task. The complexity of configuration management is not only due to the existence of a huge set of configuration parameters, but also the existence of implicit dependencies between these parameters. Network administrators are continuously requested to conduct provisioning or performance tuning. However, changing one configuration parameter may bring a complex chain of changes that network administrators must anticipate it. As networks grow larger, configuring and debugging these networks become too complicated. The complication is getting worse when the network is composed of multi-vendor network devices. Consequently, network administrators, who rely on CLIs, need to remember a myriad of commands, protocols, and device architectures. This certainly causes a critical problem for market demands which require quick and accurate deployment of new services to maintain the revenue.

All these complications increase the chances of faulty configurations. The study in [70] revealed that network administrator errors are the largest cause of network failure (around 61%) as shown in Figure 1.1. Analysis from IT experts states that human errors are responsible for 50 to 80 percent of network device outages [93]. In 2010, Arbor Networks [2] has published a security survey report. The participants of the survey were from Tier 1, Tier 2 and other IP network operators. Even though the report was focusing on security issues, 61% of survey participants indicated that misconfiguration is the most significant

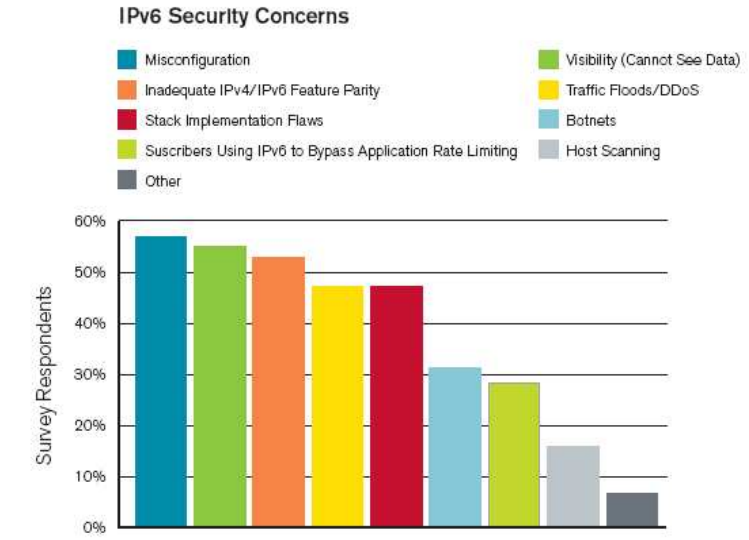


Figure 1.2: IPv6 Security Concerns

operational threat encountered during 2010. The interesting point mentioned in the report is that 57% of respondents stated that misconfiguration resulting in outages are their foremost security concern related to IPv6 (see Figure 1.2). Hoelzle and Barroso have reported that misconfiguration is the second major cause of service–level failure at one of Google's service [38]. Recently, the study in [96] has indicated that Amazon's cloud service, Microsoft Azure and Facebook have experienced several service disruptions due to misconfiguration that affected millions of their customers.

Misconfiguration is costly since network and support engineers need to spend considerable time to debug and fix them. The report in [70] has indicated that 75% of all Time to Repair hours are due to human errors. Another study has shown that 80% of IT budgets in enterprise networks are dedicated just to maintain the current operating environments [54].

The increasing complexity along with high-percentage of administrator errors points towards an inevitable need to automate network configuration management. Automating network configuration has the following potential advantages [22]:

- It reduces the time required to perform a given task.

- It reduces the percentage of administrator error.
- It guarantees consistent configuration across an entire network.
- It provides accountability for changes.

The management of network devices is mostly performed by tools provided by the equipment vendors. These tools are designed based on either the SNMP framework or proprietary frameworks. SNMP-based tools have the limitation that they do not treat a network as a uniform entity, but rather they interact with one network element at a time. Proprietary-based tools have the limitation that they cannot be used in heterogeneous networks.

There are a plethora of other configuration management tools that simplify the configuration of devices in an environment where there are a large number of heterogeneous devices. These frameworks are centered on the idea of reducing complexity through abstraction and separation of concerns. The objective of abstraction is to describe the operational requirements without diving down into how to achieve those requirements. However, due to the sophistication of current network services, the ability to check and examine how a service is configured is in fact critical to troubleshooting, debugging and quickly achieving the desired effect. We believe that choosing the right level of abstraction is a key feature of a successful management system. The abstraction should be low enough to the current configuration management approach and high enough to capture the complexity of configuration tasks.

In 2006, the Internet Engineering Task Force (IETF) published a new configuration protocol called NETCONF [27]. In 2010, IETF published its associated data model, which is known as YANG [11]. NETCONF resolves the limitations found in SNMP protocol and together with YANG can make a powerful contribution in designing an efficient management system . In fact, NETCONF and YANG are specifically designed for the task of network configuration, and they are resulted from a series of recommendations of network operators and experts. Several major network equipment vendors are already supporting these standards in their devices [15]. Although, NETCONF and YANG provide a standardized abstraction

for low-level configuration tasks in multi–vendor networks, we still need to find a suitable abstraction to close the gap between high–level requirements and NETCONF/YANG abstraction.

1.2 Problem Statement

Network configuration management is considered the most complicated task among other network management tasks. The inadequacies of current network configuration approaches have forced network operators to perform configuration tasks manually via CLIs. Several studies have shown that misconfiguration is the most significant threat for network operation and the main cause of network outage for many network environments. Moreover, networks are configured to satisfy certain requirements. Requirements include performance, connectivity, fault tolerance, security, provisioning, etc. The gap between high-level requirements and low-level configuration data is difficult to close or bridge.

The aim of this dissertation is to develop an automated management system to enhance network configuration management. Our objective is how to build a system that has the following features:

- Scalability - It should accommodate all sizes of networks.
- Comprehensive - It should take into account the other management functions.
- Adaptable - It should accommodate new equipment or technology.
- Intelligent - It should minimize the human intervention by automating decision making.
- Interoperability - It should follow the standards to accommodate heterogeneous network environments.

1.3 Scope

The scope of this dissertation is limited to improving network configuration management. It does not focus on how to detect and analyze errors, how to assess network performance, or how to guarantee service level agreement.

We assume that the management system has multiple subsystems that will handle the other aspects of management functions, such as detecting faults, performance measuring, etc. However, this dissertation provides a recommendation on how to develop such components to work as a coherent complete system. The configuration management system relies on these subsystems in order to maintain the network operational state.

The work in this dissertation is not focusing on systems management, which is pertaining on anti-virus management, user's activities, storage management, etc. Eventually, network management environment is more stringent than systems management environment in the sense that we do not have the freedom to install new software on network devices. We are limited to the services that are provided on the network devices.

Finally, the work in this dissertation is limited for managing IP networks. It has limited support for non-IP telecommunication networks.

1.4 Goals and Contributions

The dissertation describes a series of efforts to understand, manage, augment, verify and automate network operations. The overarching goal is to build a comprehensive automated configuration management system called AutoConf. AutoConf performs four management functions: configuration change management, verification management, automation management and resource discovery management. Therefore, we summarize our contributions as follows:

- Extensive literature review that covers the contributions of standard bodies in network configuration management.

- Proposing a new configuration semantic model to logically link between the management functions.
- A solution for resource discovery management based on NETCONF/YANG framework.
- A comprehensive verification management that covers configuration data verification and network behavior verification.
- A new set of formal models to represent firewall, routing and NAT policies.
- A solution for supporting dynamic networks based on reinforcement learning.
- A network topology generator tool to evaluate the scalability of AutoConf with large networks.
- A policy–state generator tool to evaluate the efficiency of AutoConf to analyze large set of policy rules and network state.
- A series of case studies on different configuration scenarios to illustrate the flexibility of using AutoConf. The case studies include:
  - RIP routing configuration,
  - OSPF routing configuration,
  - MPLS VLAN configuration, and
  - Bridge configuration.

1.5 Organization

This dissertation is organized as follows. Chapter 2 provides the necessary background to understand the concepts used in later chapters as well as a literature review. Chapter 3 defines the model and the framework that will be used to automate network configuration

management. The automated system is divided into a set of components: change configuration, verification analysis and configuration automation. The same chapter provides how to handle configuration change. In Chapter 4, we describe the configuration verification system. Then, we describe configuration automation in Chapter 5. The implementation of AutoConf will be discussed in Chapter 6. In Chapter 7, we summarize our results where we evaluate the AutoConf system on a set of case studies along with simulation models. We conclude our dissertation in Chapter 8.

Chapter 2

Background and Literature Review

The design of our management system is built upon Binary Decision Diagram (BDD) and reinforcement learning (RL) techniques. As such, we start this chapter with a quick introduction to BDD and RL techniques. Then, we provide an overview of major network management architectures and protocols. We focus on those architectures that have been developed by standardized organizations such OSI, TMN and IETF. Our management system uses the NETCONF protocol to communicate with managed devices. We give a detailed description of the NETCONF protocol and its operations. We conclude this chapter by presenting recent research work in network configuration management proposed in academia and vendor operators' communities.

2.1 Binary Decision Diagram

Network devices handle complex policies such as filtering, routing, etc. Let us consider the following example that represents a filtering policy as shown in Table 2.1:

The example shows two rules. The first rule accepts any TCP traffic originated from subnet 200.100.2.0/25 to the web servers in subnet 11.24.0.0/16. However, the second rule denies any packet originated from subnet 200.100.2.0/25 when it tries to access ports from

constraint	action
tcp 200.100.2.0 255.255.255.128 any 11.24.0.0 255.255.0.0 80	accept
any 200.100.2.0 255.255.255.128 any 11.24.0.0 255.255.0.0 1-1024	deny

Table 2.1: Sample of filtering policy

1 to 1024 of any machine in subnet 11.24.0.0/16. The order of filtering rules is critical. If a packet matches the first rule, then it will be accepted. Otherwise, the packet will be matched with the second rule. If we change the order of the two rules, then the first rule will never be matched.

Network devices may store thousands of such rules. If a network has hundreds or thousands of devices, how can we verify connectivity and security requirements? What should our overall strategy be? Consider Figure 2.1 that shows a real and a formal worlds. Given we want to find a real world solution as indicated by edge (1). However, in practice it is hard to solve problems in the real world. One approach is to formalize the problem using a formal model (edge 2). Within the formal world, we can solve the formal problem in feasible time (edge 3), and transform the formal solution back to a real solution (edge 4).

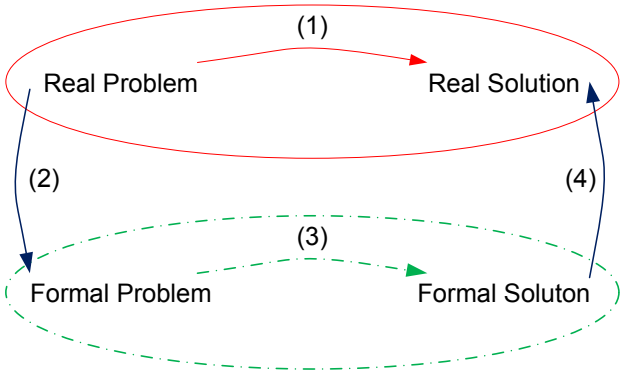


Figure 2.1: The real and formal worlds illustrated by two circles.

The route 2–3–4 might seem as detour over just taking edge 1. But going via the formal world, we can quickly reason about our methods. In this dissertation, we use the Binary decision diagram, or simply BDD, as our formal world.

Basically, BDD is a directed acyclic graph (DAG) data structure, which was introduced

for compact and canonical representation of Boolean function f over a set of binary variables $x_1, x_2, \cdots, x_n$ where $x_i \in \{0, 1\}$. For example, $f(x_1, x_2, x_3) = x_1 \wedge \bar{x_2} \vee x_3$. The role of BDD is to define a compact procedure for determining the binary value of f given the binary values of x_1, x_2, and x_3. One way to do this would be to begin by looking at the value of x_3. If $x_3 = 1$, then $f = 1$ and the procedure is done. If $x_3 = 0$, we look at x_2. If $x_2 = 1$, then $f = 0$. Otherwise, we look at x_1 and its value will be the value of f.

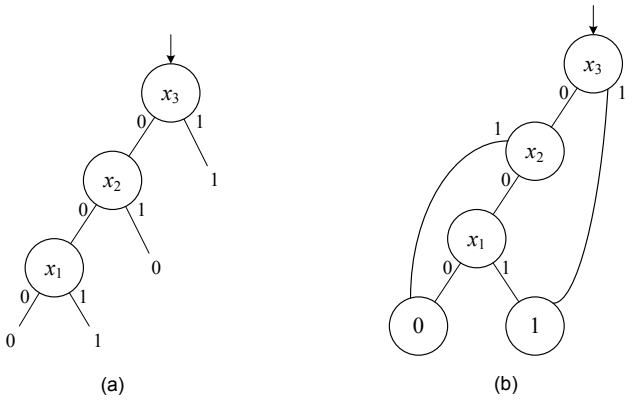


Figure 2.2: Decision diagram for $x_1 \wedge \bar{x_2} \vee x_3$

Figure 2.2(a) shows a simple diagram of this procedure. We enter at the node indicated by the arrow and then simply proceed downward through the diagram, noting at each node the value of its variable and then taking the indicated branch. When a 0 or 1 value is reached, this gives the value of f and the process ends.

Formally, we define BDD as a DAG consisting of one source node (called root node), multiple internal nodes, and two sink nodes which are labeled as 0 and 1. For example, the formal BDD representation of $f(x_1, x_2, x_3) = x_1 \wedge \bar{x_2} \vee x_3$ is shown in Figure 2.2(b). Each internal node may have multiple parent nodes, but it has only two children nodes. Each path from the root to the sink node 1 (or the sink node 0) gives a true (or false, respectively) output of the represented Boolean function. A BDD is called *ordered* if the label of each internal node has a lower index than the label of its children nodes. Being canonical, each BDD identified by its root node is unique. In other words, if f_1 and f_2 are two Boolean functions such that $f_1 \leftrightarrow f_2$, then the BDD of f_1 is identical to the BDD of f_2 with the same

root node (given the same order of their binary variables).

BDDs allow logical operations on Boolean functions, such as AND, OR, and XOR, to be performed in a polynomial time with respect to the number of nodes. Existing BDD packages allow fast manipulation. In particular, the package that we use BuDDy [28] implements hash tables along with cache memory for fast retrieving and traversing BDD graphs.

The main advantage of using Boolean function is to represent compactly complex constraints that compose of several conditions like the filtering policy shown in Table 2.1. This research work uses BDD for this purpose. So, in the remaining of this section, we explain how we model constraints using BDD.

For the sake of simplicity, let us consider a constraint that has three fields (or conditions): 3-bit IP address, 2-bit port and 1-bit protocol. The number of bits required to encode the constraint is 6 bits. As such, we need 6 Boolean variables as shown in Table 2.2.

Field	Boolean Variables	MSB	LSB
IP address	x_0, x_1, x_2	x_0	x_2
Port	x_3, x_4	x_3	x_4
Protocol	x_5	x_5	x_5

Table 2.2: Boolean variables distribution over constraint fields. Most significant bit (MSB) and Least significant bit (LSB) are shown

Let us consider the following filtering constraint: IP address = 4/2 (in CIDR notation), Port = 3 and Protocol = 0. This constraint can be encoded into BDD using the following expression:

$$C = (x_0 \wedge \neg x_1) \wedge (x_3 \wedge x_4) \wedge \neg x_5$$

The filtering policy can match two packets: (1) IP address = 4, Port = 3 and Protocol = 0, and (2) IP address = 5, Port = 3 and Protocol = 0. Notice that the Boolean variable x_2 does not affect the satisfiability of C. Using C, we can perform several queries like (1) how many packets are matching the constraint C, and (2) given a packet p, does p match C? The second query can be answered by finding $p \rightarrow C$. If the result is *true*, then there is

a match. Also, notice that a Boolean function can have a very compact form when a field has a range of values. For example, the network address 4/1 represents a subnetwork where the first IP address is 4 and the last IP address is 7. The Boolean function to represent this range of addresses is just x_0.

2.2 Reinforcement Learning

Reinforcement Learning is a branch of Artificial Intelligence techniques for learning by interaction with an environment to accomplish a specific goal. There are three main components in the RL framework: an agent, an environment and a scalar reward. The agent makes a decision by taking an action at every time–step according to a policy and expects a feedback in terms of a scalar reward for every action.

In RL literature, there are two types of problems where RL provides attractive solutions [85]:

1. Policy evaluation, which refers to the techniques of evaluating the consequences of taking actions according to a fixed policy, and

2. Policy control, which refers to the techniques of finding an optimal policy (π^*) that maximizes the received rewards in a long run.

Therefore, in this dissertation, we just consider the techniques for solving control problems; specifically we consider RL techniques that are based on temporal difference (TD) methods. They are used to find the optimal policy that does not require any assumption except visiting all states in order to converge to optimal policy. The most well-known approaches that are based on TD are TD(λ), Sarsa and Q-learning. They offer a solution to systems and networks management that differs from *supervised* machine learning techniques. TD techniques can learn optimal policy with little or no built-in system-specific knowledge. Later, we show the difference between TD(λ), Sarsa and Q-learning.

Several researches and case studies [88] have shown the promise of using TD in automating networks and systems management. In the following paragraphs, we give a formal description of RL problems.

RL considers a finite Markov decision process (MDP) in which there is a transition from state to another state when a learning agent takes an action. Let $\mathcal{S}$ be the set of all possible states an environment can be in and let $\mathcal{A}$ be the set of all possible actions an agent can take. At each time-step $t = 0, 1, 2, \cdots$, the environment is in state $S_t \in \mathcal{S}$. According to a policy π, the agent selects an action $A_t \in \mathcal{A}$ and then receives a feedback (or a reward) in terms of $R_t \in \Re$. By taking the action A_t, the environment transits to a new state $S_{t+1} \in \mathcal{S}$.

The ultimate goal of the learning agent is to maximize the received rewards resulted from a long run (i.e., not only the immediate reward). This can be achieved by using a value function that follows Bellman Equation [85]. In our case, the value function is called state-action value and denoted as $Q(s, a)$, which means the value of taking action a in state s. The difference between Sarsa and Q-learning is how $Q(s, a)$ is computed. In Sarsa, $Q(s, a)$ is based on the next action (not necessarily to be the optimal action) to be selected. While in Q-learning, the value of $Q(s, a)$ is based on the optimal action when visiting the next state. In other words, Q-learning simply assumes that an optimal policy is being followed. Therefore, Q-learning method is more convenient than Sarsa when applied to network management. We need to take into consideration the knowledge of network administrators captured in the input policy π.

Generally, the state-action value of a policy $\pi : \mathcal{S} \rightarrow \mathcal{A}$ is defined as

$$Q^{\pi}(s, a) = \mathbb{E}\left[\sum_{t=0}^{\infty} \gamma^t R_{t+1} | S_0 = s, A_0 = a, \pi\right] \tag{2.1}$$

where γ is a discount factor between 0 and 1 expressing how strongly present value relies on future rewards and $\mathbb{E}[.]$ denotes expectation over random samples generated by following policy π. The state–action value, $Q(s, a)$, measures how good it is for the management system to execute action a in a given state s. Several powerful theorems guarantee that Q-learning converges with probability of 1 to optimal policy that achieves lots of rewards in

the long run. In this case, the optimal action at a given state is the action with the highest $Q(s, a)$ value. Therefore, the optimal action-value function, denoted as Q^* is

$$Q^*(s, a) \stackrel{def}{=} \max_{\pi} Q^{\pi}(s, a), \forall s \in \mathcal{S}, \forall a \in \mathcal{A}.$$

In this dissertation, we consider policy–based management as an approach to controlling the network behavior dynamically. In this context, a policy is a set of rules such that each rule is expressed as $C_1, C_2, \cdots, C_N \Rightarrow A_1, A_2, \cdots, A_M$, where C_i is a logical condition, A_j is an action, and N and M are positive integers. If a rule is triggered, the management system should decide to select an action j among M actions. If multiple rules are triggered, the management should decide the optimal plan to reach to a given desired state. We use RL to guide our management system to make the optimal decision based on the current network operational state. There are several issues that we must address to have a successful RL implementation:

- As we mentioned the goal of an agent is to find the maximum $Q(s, a)$. Therefore, the learning agent should try all possible actions in order to discover the action that has maximum $Q(s, a)$. As a result, the learning agent is often faced with a dilemma: whether to *exploit* the current knowledge (i.e., current $Q(s, a)$) to select the best action, or to *explore* new knowledge by trying actions that have not yet been tried. The most widely used approach to balancing between exploration and exploitation is called ϵ-greedy [85]. In this approach, the system performs exploration with probability of ϵ and exploitation with probability of $1 - \epsilon$. A typical value of ϵ is 0.1.

- Moreover, when learning online in a live system, any poor action the agent makes can result in quite poor rewards, and the cost of this can prohibit an online learning approach.

- RL framework can be a complex due to huge number of (state, action) pairs and state transitions to converge to optimal policy.

In Q-learning, Equation 2.1 is approximated using the following expression:

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha \left[R_{t+1} + \gamma \max_{a_{t+1}} Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t) \right] \tag{2.2}$$

where α is called step size constant. However, we consider Dyna-Q approach (enhanced Q-learning) since it has the capability to learn network's dynamics on-line by building a partial model plan [74, 84, 85]. It has been shown that Dyna-Q has significant accelerated learning process. Briefly, Dyna-style learning is based on a model that is updated continually at each time-step by navigating and propagating the action "goodness" to some steps in the history. In Chapter 5, we discuss this algorithm further when we build an automated configuration management system.

2.3 Network Management Architectures

This section analyzes the current technologies in network management in general while we give more attention to the efforts that have been done in network configuration management. We start with the efforts of organizations that have developed protocols and architectures for network management. The well-known organizations that have significant contributions to networks management are:

- The International Organizations for Standardization (ISO).
- The Telecommunication Standardization Sector (T) of the International Telecommunication Union (ITU).
- The Internet Engineering Task Force (IETF).
- Distributed Management Task Force (DMTF).

Due to their efforts, networks, in essence, can be broadly classified into two categories: telecommunication networks and IP networks. ISO and ITU-T provide solutions for telecom-

munication networks while IETF provides solutions for IP networks. DMTF focuses on systems management in enterprise IT environments.

2.3.1 OSI Management

OSI management was first introduced as part of the Open System Interconnections (OSI) program, *Basic OSI reference model* [43]. OSI management is defined as the facilities to control, coordinate and monitor the resources which allow communications to take place in the OSI environment (OSIE) [44]. The origin of OSI management can be found in ISO; however, most of the work is performed in collaboration with ITU-T. Within ITU-T, OSI management is defined in X series of Recommendations.

Both bodies proposed two standards that form the basis for OSI management: OSI management framework [44] and System Management Overview [40]. In addition, there are several standards that provide more details about management functions and information exchanges.

The objective of OSI management as mentioned in [44] is to support user's needs for what is presently known as the five functional area of OSI:

- Fault management
- Configuration management
- Account management
- Performance management
- Security management

The term 'FCAPS' is commonly used to denote these areas. To deal with the OSI management, we should first understand the terminologies used by the OSI standards that are related to the network management. An *open system* is any network component; whether this component is a bridge, a switch, a router, or a workstation using OSI protocol stack.

Any two devices that communicate via the OSI protocol at the same OSI Reference Model layer are called *peer open systems*.

ISO in collaboration with ITU-T specifies four aspects to describe System Management Model. These aspects are: information aspects, functional aspects, OSI communication aspects, and organizational aspects. The following is a description for each aspect.

2.3.1.1 Information Aspects

The individual open system within the OSIE may have a set of resources that need to be managed such as a layer entity, a connection, a physical communication equipment. These resources are viewed as *managed objects* (MOs). That is, managed objects are abstractions of data processing and data communications of resources for the purpose of management. OSI MOs can be specific to an individual layer, in which case they are called (N)-layer MOs managed by layer management protocol and services. Otherwise, they are called systems MOs which are managed by system management protocol and services. The set of all managed objects within an open system constitutes that system's management information base (MIB).

Conceptually, a managed object has the following associated characteristics as depicted in Figure 2.3:

- attributes, which are the properties of the MO,
- operations, which are applied to the MO,
- behavior, which is exhibited by the MO, and
- notifications, which are emitted by the MO.

The Structure of Management Information (SMI) standard provides a fine-grained data definition for MOs. It models managed objects by using object-oriented paradigm [41]. Each MO is an instance of *managed object class*. A class is a collection of *packages*, each of which

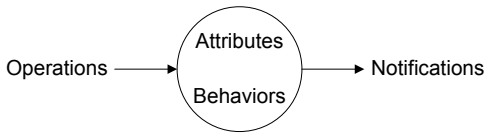


Figure 2.3: OSI abstraction for managed objects

is defined to be a collection of attributes, operations, behavior and notifications. Packages are either mandatory or conditional upon some explicitly stated condition. When a new MO is created, it must contain all mandatory packages and those packages for which the explicit condition associated with them in the managed object class definition is evaluated to TRUE.

Attributes are defined by using ASN.1 notation [47]. An attribute can be a *single-valued* or a *set-valued*. A group of attributes sharing the same behavior can be aggregated together to constitute a structured-valued attribute called *attribute group*. Moreover, an attribute group can have a fixed set of attributes or an extensible set of attributes as a result of inheritance.

SMI standard has defined two types of operations: operations related to MO's attributes and operations related to MO as a whole. The operations that can be applied to MO's attributes are:

- `get`: to retrieve an attribute value,
- `replace`: to modify an attribute value,
- `replace-with-default`: to replace an attribute value with its default value,
- `add`: to insert a member value to a set-valued attribute, and
- `remove`: to remove a member from a set-valued attribute.

The operations that can be applied to a MO as a whole are:

- `create`: to create new instances of the MO,

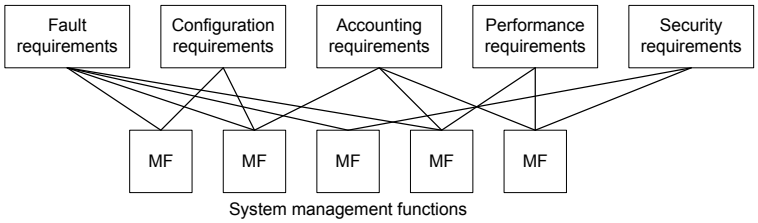


Figure 2.4: Relationships between management functions and user requirements

- `delete`: to delete the MO, and
- `action`: for user-defined operation

Finally, a MO can exhibit any of the following behavior:

- Imposing semantic and consistency constraints on attributes.
- Establishing dependency relationship between attributes; taking into account the presence or absence of conditional packages,
- Determining how the MO responds when it receives management operations.
- Defining the situation under which notification will be triggered.
- Defining the preconditions and the postconditions that constraint the validity of operations and notifications.

2.3.1.2 Functional Aspects

Management activities are modeled as a set of system management functions (MFs), each of which is satisfying certain user requirements. For example, reading an error counter (as a function) could be used for fault management or performance management. Similarly, a user requirement may require more than one management function to be satisfied. Figure 2.4 shows many-to-many relationship between management functions and requirements.

ISO and ITU-T have developed a set of standards specifying standard system management functions. Within ISO, management functions are defined in ISO/IEC 10164 while

Title	ISO/IEC	ITU-T
Object management function	10164-1	X.730
State management function	10164-2	X.731
Attributes for representing relationships	10164-3	X.732
Alarm reporting function	10164-4	X.733
Event report management function	10164-5	X.734
Log control function	10164-6	X.735
Security log function	10164-7	X.736
Security audit trail function	10164-8	X.740
Objects and attributes for access control function	10164-9	X.741
Usage metering function for accounting purpose	10164-10	X.742
Metric objects and attributes	10164-11	X.739
Test management function	10164-12	X.745
Summarization function	10164-13	X.738
Confidence and diagnostic test categories	10164-14	X.737
Scheduling function	10164-15	X.746
Management knowledge management function	10164-16	X.750
Change over function	10164-17	X.751
Software management function	10164-18	X.744
Management domain and management policy management function	10164-19	X.749
Time management function	10164-20	X.743
Command sequencer for systems management	10164-21	X.753
Response time monitoring function	10164-22	X.748

Table 2.3: Systems management functions

within ITU-T, they are defined in ITU-T X.730-799 recommendations series. Table 2.3 shows a list of defined management functions.

2.3.1.3 Organizational Aspects

OSI System management model follows the agent-manager paradigm as shown in Figure 2.5. In case of management system, management activities are carried out by management information services (MIS-users). Management information is exchanged between two MIS-users only when one MIS-user is acting as the agent role and the other is acting as the manager role. MIS-user's role is not static. An MIS-user can change its role over time.

An MIS-user taking the role of an agent is responsible to process the received management operations on MOs. It may also forward notifications emitted by MOs to a manager. An

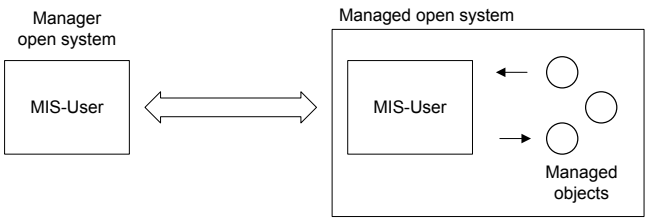


Figure 2.5: Manager-agent Interactions

MIS-user taking the role of a manger is responsible for one or more management activities, by sending management operations and receiving notifications.

The OSIE may be partitioned into a number of *management domains* in which each management domain has zero or more managed object; those MOs are referred to as members of the management domain. A managed object may belong to zero or more management domains.

2.3.1.4 Communication Aspects

The last aspects of OSI architecture are communication aspects. OSI management has introduced the concept of Systems Management Application Entities (SMAEs) to model the exchange of management information between two open systems at the application layer of OSI Reference Model. SMAE is composed of System Management Service Element (SMASE) and the Association Control Service Element (ACSE) [46]. The SMASE specifies management information and notifications to be exchanged between peer SMAEs, while ACSE establishes and closes associations between peer SMAEs.

In addition, OSI has defined the Common Management Information Service (CMIS) as the preferred communication service to exchange management information between SMASEs. CMIS definition follows the standard definition of OSI-service as described in [42]. An application that uses CMIS services is called Common Management Information Service Element (CMISE). There are two types of CMISEs: CMISE-service-user and CMISE-service provider. CMISE-service-user uses CMIS services to communicate to CMISE-service-provider. It is worth to mention that SMASE may use communication services other than CMISE such as

File Transfer, Access and Management (FTAM) [45] or Transaction Processing (TP) [39].

The CMIS standard defines the following service primitives:

- *M-GET*: to retrieve management information.
- *M-CANCEL-GET*: to cancel a previously invoked M-GET. If, for example, M-GET delivers too much information such an entire routing table, a manager can send M-CANCEL-GET to stop the transmission
- *M-SET*: to modify an attribute or a set of attributes of a MO.
- *M-ACTION*: to perform some actions defined on a MO.
- *M-CREATE*: to create a new instance of a MO.
- *M-DELETE*: to delete an existing MO.
- *M-EVENT-REPORT*: to report the occurrence of some kind of events as a notification.

2.3.2 TMN management

The concept of Telecommunications Management Network (TMN) was introduced by ITU-T and defined in Recommendation M.3010 [48]. Conceptually, TMN is a separate network that interfaces a managed telecommunications network at several different points. Figure 2.6 shows a typical managed telecommunication network using TMN framework.

TMN management uses different terms than OSI management. A network is generally consists of many types of analogue and digital telecommunications equipment as well as supported equipment. These equipments are referred to as *Network Elements* (NEs). Managers are referred to either as *Operations Systems* (OSs) or *Workstations* (WSs). The difference between OS and WS is that OS is fully conformed to TMN standards while WS is partly conformed to TMN standards and usually belongs to another non-TMN network. Managers and NEs are communicated via a Data Communication Network for the purpose of management.

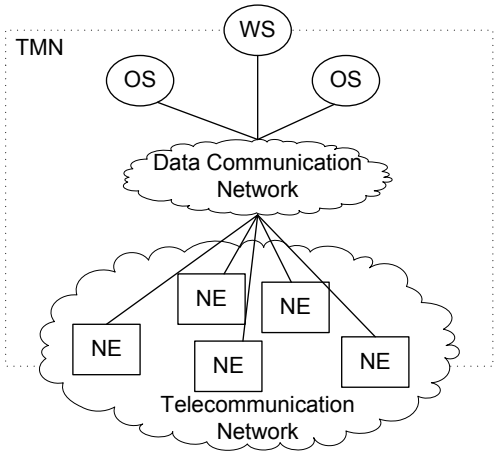


Figure 2.6: TMN network management concept

The basic objective of the TMN framework is to provide generic network models for managing diverse equipment, network and services using generic information models and standard interfaces. The framework also takes into consideration the management of individual NE which has a coordinated effect upon the network. It consists of several management architectures at different levels of abstraction: functional architecture, physical architecture and information architecture. In addition, it provides a logical reference model for partitioning of management functions which is called Logical Layered Architecture (LLA).

Before describing TMN framework, it is worth pointing out that the original TMN framework has been changed from its original framework as found in M.3010 1992. The latest updated version of M.3010 was published in 2000. This review considers the latest version of TMN Recommendations.

2.3.2.1 Functional Architecture

Functional architecture is an architectural model that identifies TMN functions, interactions and corresponding management requirements. There are three categories of functions in any managed telecommunications network: telecommunication functions, TMN management functions and support functions. Telecommunications functions, which provide telecommunications services, are not part of the TMN standardization but are represented

to the TMN for the purpose to be managed. TMN management functions are responsible to monitor and control the telecommunications network as well as the TMN network itself. Support functions, which may optionally be found in the TMN, provide additional functionality to support the management functions such as data communication functionality, database functionality, user interface functionality and security functionality.

Functional architecture provides a conceptual model of TMN functionality and has the following fundamental elements:

- Function blocks,
- Management Application Function,
- TMN management function sets, and
- Reference points.

In the following paragraphs, we give a brief description for each element.

Function blocks. Function blocks organize management functionality based on the role of its functions. TMN standard defines a function block as the smallest deployable structure of TMN management functionality. There are four types of function blocks:

- Operations Systems Function block (OSF), which includes management functions to manage and control NEs and TMN itself (other OSs).
- Network Element Function block (NEF), which provides telecommunication and support functions to facilitate OSF to manage NEs.
- Workstation Function block (WSF), which supports WSs to translate between a TMN reference point and a non-TMN reference point.
- Transformation Function block (TF), which connects between two functional entities with incompatible communication mechanism. The TF may be used to connect two

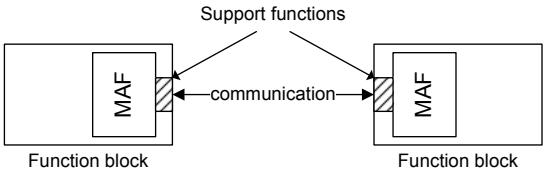


Figure 2.7: MAFs interactions

function blocks (either both of them inside TMN or one of them located outside of TMN) each of which supports a standardized, but different, communication mechanism. Also, the TF may be used to connect a function block with a standardized communication mechanism in a TMN to a functional entity with a non-standardized communication mechanism in a non-TMN network.

Management Application Function (MAF). MAF represents the functionality of one or more TMN management services. TMN can be divided into a set of telecommunication managed areas where a managed area can range from a single NE to a very complex network. Each of these managed areas supports one or more TMN management services such as network provisioning management, traffic management, routing management, and logistics management. ITU-T Recommendations M.32xx enumerates the identified TMN managed areas as well as the MAFs with respect to the technologies and services supported by the TMN.

To understand the remaining functional elements, let us consider the diagram in Figure 2.7 that shows the relationship between function blocks, MAFs and support functions. The interactions that take place between MAFs in different TMN function blocks are referred to as TMN management functions.

TMN management function sets. The collection of all TMN management functions used to accomplish the functionality of a single MAF (or management service) is referred to as TMN management function set. ITU-T Recommendations M.3400 provides a library of general TMN management function sets and their TMN management functions members.

	NEF	OSF	TF	WSF	non-TMN
NEF		q	q		
OSF	q	q or x	q	f	
TF	q	q	q	f	m
WSF		f	f		g
non-TMN			m	g	

Table 2.4: Relation between function blocks expressed as reference points

Reference points. The concept of reference points was introduced to standardize the interactions between function blocks. A reference point represents an external view of a particular pair of function blocks. Different external views have been defined. One external view is the aggregation of all abilities offered by a particular function block to another function block. A second external view is the aggregation of all management operations between function blocks. A third external view is the aggregation of all notifications emitted from one function block to another function block.

Five different classes of reference points are identified. Three of them (q, f and x) are TMN reference points; the other classes (g and m) are non-TMN reference points. The relationship between reference points and function blocks is illustrated in Table 2.4. The table illustrates all of possible pairs of TMN function blocks that can be associated via a reference point. A function block at the top of a column may exchange management information with a function block at the left of a row over the reference point that is mentioned at the intersection of the column and row. if the intersection is empty, the associated function blocks cannot directly exchange management information between each other. Reference point x is applied only when each OSF is in different TMN.

2.3.2.2 Information Architecture

For information architecture, TMN standardization did not develop its own specific information model but built upon industry recognized solutions that are based on object-oriented paradigm such as OSI management information model and CORBA-based infor-

mation model.

2.3.2.3 Physical Architecture

The purpose of physical architecture is to implement the functional architecture where the implementations rely on the underlying physical equipment. Therefore, TMN physical architecture is defined at a lower abstraction level than TMN functional architecture.

The physical model has the following fundamental elements: building blocks (physical equipment) and interfaces. A building block is responsible to implement at least one function block while interfaces are responsible to implement reference points. The physical model defines seven building blocks:

- Operations System (OS), which implements OSFs(m)[1] as well as TFs and WSFs.
- Q-Adapter device (QA), which implements TFs when TFs connect a TMN function block with a non-TMN function block at m interface having TMN communication standard.
- X-Adapter device (XA), which implements TFs when TFs connect a TMN function block with a non-TMN function block having non-TMN communication standard.
- Q-Mediator device (QM), which implements TFs when TFs connect between TMN function blocks having incompatible communication mechanism and both function blocks are on the same TMN.
- X-Mediator device (QM), which implements TFs when TFs connect between TMN function blocks on different TMN having incompatible communication mechanism.
- Network Element (NE), which implements NEFs(m) as well as TF, OSF and WSF.
- Workstation (WS), which implements WSFs only.

[1] m between parenthesis means mandatory

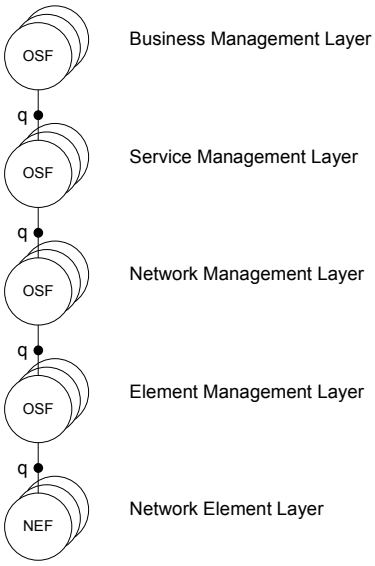


Figure 2.8: TMN Functional Layering

In order for two or more physical blocks to exchange management information, they must agree on a unified interface to communicate. We can imagine interfaces as the implementations of communication services within the protocol stacks. TMN standardization defines three interfaces corresponding to the reference point that implements: Q interface, F interface and X interface.

2.3.2.4 Logical Layered Architecture

To deal with complexity of management, TMN framework introduced the concept of Logical Layered Architecture (LLA) to organize the TMN management functions using different levels of abstractions. LLA organizes functions into a set of management function layers. Five layers have been defined, which are: Business Management Layer, Service Management Layer, Network Management Layer, Element Management Layer and Network Element Layer. These layers along with their function blocks and reference points are shown in Figure 2.8.

The bottom of the management layers is network element layer. This layer contains NEFs. These functions are managed by OSFs at Element management layers via a q ref-

erence point. Element OSFs, which concerns the management of individual NE, in turns, are managed by OSFs at network management layer. Network OSFs cover the realization of network-based TMN application functions by interacting with Elements OSFs. Thus, the Element and Network OSFs provide the functionality to manage a network by coordinating activities across the network and supporting the services offered by the network. Service management layer concerns with services offered by one or more networks and normally performs a customer interfacing. Finally, business management layer concerns with the management of the whole enterprise and carries out an overall business coordination.

2.3.3 Internet Management

The concept of Internet-based management was introduced by Internet Engineering Task Force (IETF). In contrast to OSI approach, IETF did not define a specialized standard for Internet Management Architecture. Current Internet management architectures are tailored based on the underlying communication protocols. The main two communication protocols defined by IETF for the purpose of exchanging management information are Simple Network Management Protocol (SNMP) and NETwork CONFiguration Protocol (NETCONF).

The Internet management architecture that is based on SNMP framework is called Internet Standard Management Framework or simply SNMP framework. For the NETCONF, up to writing this dissertation, there is no proposed management architecture for NETCONF. Therefore, the remaining of this section will concentrate on the Internet Standard Management Framework.

IETF has defined three versions of Simple Network Management Protocol: SNMPv1, SNMPv2 and SNMPv3. Regardless of SNMP versions, the fundamental elements of Internet Standard Management Framework are the same in the three versions [17], which are:

- A set of SNMP entities that take either the role of agent or manager. An SNMP entity with the role of agent provides remote access to SNMP entity with the role of manager. Moreover, management applications are executed at the manager side.

- A management protocol to exchange management information.
- Management information.

The specifications of the Internet Standard Management Framework are entirely information-oriented. The framework consists of the followings:

- A data definition language called Structure of Management Information (SMI).
- A definition of management information or Management Information Base (MIB).
- A definition of a protocol for information exchange called Simple Network Management Protocol (SNMP).
- Security and Administration.

2.3.3.1 Structure of Management Information (SMI)

The SMI defines precisely how managed objects are described and named for the purpose of management. SMI notations are taken from OSI's ASN.1 language. There are two versions of the SMI: SMIv1 and SMIv2. SMIv1 is described in RFCs 1155, 1212 and 1215 while SMIv2 is described in RFCs 2578, 2579 and 2580. SMIv2 extends SMIv1 by adding new data types, enhancing object definition and adding SNMPv2 node to MIB tree as we will explain later. The SMI is divided into three parts:

- Module definitions, which are used to define information modules using the SMI notation MODULE-IDENTITY.
- Object definitions, which are used to describe and name managed objects. Object definition starts with the SMI notation OBJECT-TYPE.
- Notification definitions, which are used to define events emitted by SNMP agent entity. Notification definition starts with the SMI notation NOTIFICATION-TYPE.

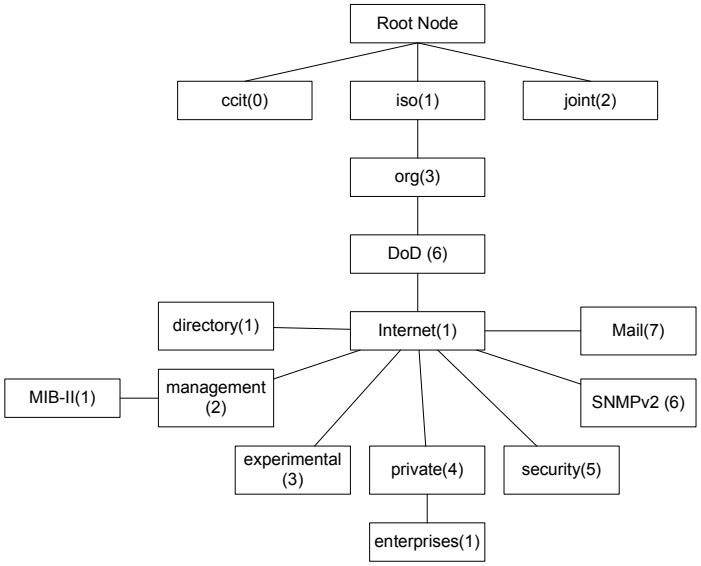


Figure 2.9: SMI object tree

To uniquely identify each managed object, the SMI introduces a naming scheme, which is basically a tree-like hierarchy. The top of the tree is called the root node and the leaves represent the actual management variables or information to be monitored or controlled. Except the root node, each node in the tree has a name and an integer number. An object ID is made up of a series of integers separated by dots based on traversing the tree starting from the root node and ending at the leaf node. Figure 2.9 shows a few top levels of this MIB tree.

2.3.3.2 Management Information Base (MIB)

To identify all managed objects that can be controlled and monitored, a large number of Management Information Base (MIB) standards have been developed. Among these MIBs is MIB-II defined in RFC 1213. MIB-II is considered the most important and probably best known MIB; it contains all information to manage the basic TCP/IP protocol suite. The structure of this MIB is simple: management information that belongs to the same protocol is aggregated together to form a group. There are nine groups defined in MIB-II: system group, interfaces group, the address translation group, the IP group, the ICMP group,

the TCP group, the UDP group, the EGP group, the transmission group and the SNMP group. The other standard MIBs contain information related to other Internet services such as routing protocols, ATM, SONET, etc. In addition, there are MIBs related to physical devices such as repeaters, switches and routers.

Next to standardized MIBs, there are also a large number of enterprise specific MIBs. Unfortunately, there is no clear structure to explain the relationships between these MIBs; the only indication of a MIB's purpose is its name.

2.3.3.3 Protocol Definition

SNMP entities that take the role of agent may have a set of standard MIBs and enterprise specific MIBs that need to be controlled and monitored. The SNMP standard defines a set of operations applied to the Object IDs found in MIBs. There is no SNMP operation to create or delete Object IDs. Also, SNMP defines only one operation (called set) to control an Object ID. We will discuss SNMP protocol in more details in section 2.4.2.

2.3.3.4 Security and Administration

The original SNMP framework (SNMPv1) had a simple authentication scheme in which two SNMP entities exchange a password called community name. The problem is that community string names are transmitted in plain text. Any attacker who sniffs the network can easily discover the password. In addition, management information is exchanged without any encryption. These weaknesses allow several threats on the network management such as masquerading, modification of information or even packet reordering.

SNMPv2 framework revises version 1 and introduces a new scheme called party-based security (RFC 1441 to 1452). This version is known as SNMPv2p. However, because of the extensive and complicated security model, SNMPv2p was not well received in the market. Attempts at simplifying the proposal were undertaken and other developments were produced under the names SNMPv2*, SNMPv2u and SMNPv2c. SNMPv2u is based

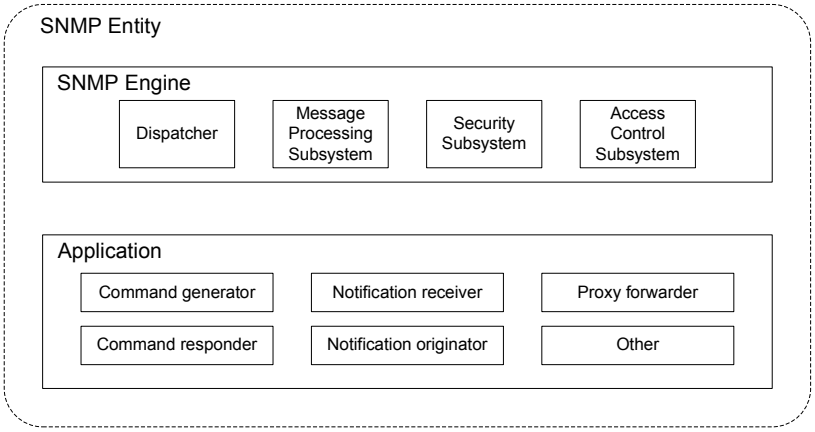


Figure 2.10: SNMPv3 Entity

on a user-oriented security model while SNMPv2c is based on community strings similar to SNMPv1 [37]. Needless to say, this proliferation resulted in market confusion and motivated IETF to introduce SNMPv3.

SNMPv3 is the latest version of SNMP. Its main contribution to network management is security. It provides message integrity, authentication and encryption. SNMPv3 introduces two concepts: security model and security level. Security model is an authentication strategy that is set up for a user and a group in which the user resides. A security level is the permitted level of security within a security model. Together will determine which security mechanism is employed when exchanging management information [25].

SNMPv3 entity has a single engine to perform the message processing as shown in Figure 2.10. When an application wants to send SNMP PDUs to the other SNMP entity, the engine first accepts the SNMP datagram to be sent from SNMP application level, performs the appropriate security functions, encapsulates the PDU into an SNMPv3 message, and finally dispatches the message out to the network. When the engine receives an SNMPv3 message from the network, it performs the necessary decryption and authentication functions before passing the PDU to the SNMP applications.

2.3.4 Discussion and Critique

This section discusses some of the main problems found in the current network management architectures. The aim of this discussion is to shed some lights on the weaknesses of these architectures that will be tackled in this dissertation. We start with the problems of OSI management, then TMN management and finally Internet management.

OSI management does not follow the principle of ISO Reference Model in which the users in a particular layer has no information about other layers. However, SMAE entity at application layer can access managed objects in other layers. Another weak point of OSI's framework is that the layer protocols (such as the presentation layer or transport layer) that are being managed, are used for exchanging management information too. This dependence contradicts the coherence of the framework since SMAE application cannot send ALARM report due to a failure in the transport layer.

TMN management architecture has several advantages over OSI management. First, TMN management assumes a separation between the telecommunication network that is managed and the TMN network that transfers management information. Such separation resolves the last problem we mentioned in previous paragraph. However, having a separate network for TMN requires additional equipment and transmission media. In addition, TMN needs to be managed, which introduces an extra overhead.

The second advantage of TMN over OSI management is that TMN defines multiple architectures as opposed to OSI management, which defines only a single management architecture. Having multiple architectures is useful when handling an additional, orthogonal issue.

The last advantage of TMN is that it divides the management responsibilities into multiple layers as we discussed in Section 2.3.2.4. Having such layers, it becomes easier to distinguish various management activities that exist in real networks.

For Internet management, IETF did not define an independent standard for Internet management architecture, but rather the architecture is defined based on SNMP architec-

ture. SNMP architecture is information–oriented. The main disadvantage of SNMP architecture is the lack of a functional structure to classify thousands of management variables (defined in MIB). One advantage of SNMP architecture over other architectures is that management systems that are based on SNMP are much less expensive than management systems that are based on OSI or TMN architectures.

By analyzing the above architectures, the main issue with network management frameworks is the inability to express the requirement rules and policies, which make it impossible to use these technologies to directly change the configuration of network elements in response to a new or altered high-level requirements [81]. Our solution proposes multi-layer framework that establishes relationships between semantically-related network devices. Such relationships enable network administrators to easily express the network requirements and facilitate the automation of network configuration management.

2.4 Network Management Protocols

In this section, we consider the network management protocols that are related to network configuration management. Up to present, there are three standards of network configuration management protocols: Common Management Information Protocol (CMIP), Simple Network Management Protocol (SNMP), and Network Configuration Protocol (NETCONF).

2.4.1 Common Management Information Protocol

Common Management Information Protocol (CMIP) is an application layer protocol based on OSI reference model defined in ISO/IEC 9596-1 (ITU-T X.711) [57]. It provides an implementation for the services defined by CMIS. The specification of this protocol explains in detail the manner in which the protocol should perform for each of the CMIS services.

The CMIP protocol requires that each application entity has a CMIP machine (CMIPM) to implement CMIP protocol. CMIPM performs two functions: First, it accepts CMIS

CMIP operation	CMIS service(s)
m-Get	M-GET
m-Cancel-Get-Confirmed	M-CANCEL-GET
m-EventReport	non-confimed M-EVENT-REPORT
m-EventReport-Confirmed	confirmed M-EVENT-REPORT
m-Set	non-confirmed M-SET
m-Set-Confirmed	confirmed M-SET
m-Action	non-confirmed M-ACTION
m-Action-Confirmed	confirmed M-ACTION
m-Create	M-CREATE
m-Delete	M-DELETE
m-Linked-Reply	when one or more M-GET, M-SET, M-DELETE or M-ACTION are initiated

Table 2.5: CMIP operations and their equivalent CMIS services

requests and responses initiated by CMISE service primitives. Second, it issues CMIP PDUs initiating a specific protocol operation.

Before two CMISE-service users exchange management information, one CMISE-service user establishes an association with the other CMISE-service user using ACSE service. CMIS-service user provides user information to CMIPM, and CMIPM encodes the request using ASN.1 notation and invokes A-ASSOCIATE service primitive of ACSE. When the other end accepts the user information (and optionally accepts all access control rules), it will send the user information back to the association initiator using A-ASSOCIATE primitive again.

Once the association is established, both CMISE-service users can exchange management information using CMIP protocol. CMIPM uses the services of Remote Operation Service Element (ROSE) to convey the CMIP PDUs over the netowrk. ROSE service, in turn, encapsulates CMIP PDUs and hands them to the presentation layer protocol. Table 2.5 lists protocol operations supported by CMIP protocol.

Figure 2.11 shows the interaction pattern between two CMISE-service users. As an example, the invoking CMISE-service user (taking the role of a manager) establishes association with the performing CMISE-service user (taking the role of an agent) for the purpose

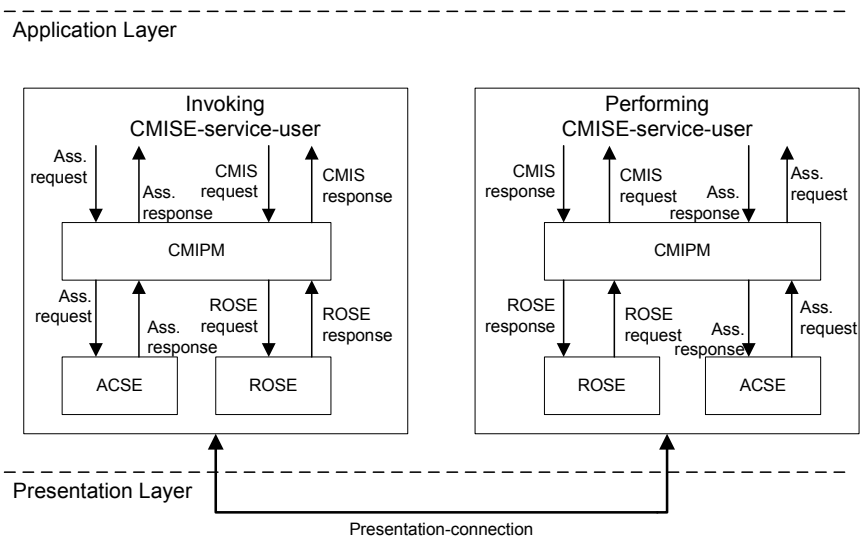


Figure 2.11: The flow model of CMIP PDUs

of reading specific piece of MIB. The manager starts by initiating M-GET *request* primitive. When the CMIPM receives the request, it constructs an CMIP-PDU requesting the m-Get operation and invokes the appropriate ROSE procedure to send the PDU. On the receipt of CMIP-PDU at the agent side requesting m-Get operation, the CMIPM checks if the PDU is well formed, issues M-GET *indication* primitive to CMISE-service user, and accepts one or more M-GET *response* primitive containing a linked-ID (to enable the recipient to correlate the reply message) followed by a single M-GET response primitive without linked-ID. The CMIPM constructs several CMIP-PDUs requesting m-linked-Reply operation for each response with linked-ID and m-Get operation for the response without linked ID. The CMIPM at the manager side receives CMIP-PDUs and issues M-GET *confirmation* primitive for each packet if the packet is well formed.

2.4.2 Simple Network Management Protocol

Simple Network Management Protocol (SNMP) is an application layer protocol based on the TCP/IP protocol suite. Since its first standardization in 1988 published in RFCs 1155, 1212, 1215, and 1157, the SNMP has become the most widely used network management

tool for Internet management.

The popularity of SNMP in the late 1980s and early 1990s led to awareness of its functional deficiencies such the inability to easily specify the transfer of bulk data and the lack of strong security model [80]. These functional deficiencies have been addressed in SNMP version 2. Due to lack of consensus and complexity of security models proposed for SNMPv2, a new IETF SNMPv3 has been defined in RFCs 2271-2275. This document set defines a framework for incorporating security features into an overall capability that includes either SNMPv1 or SNMPv2 functionality. This means that SNMPv3 defines a security model to be used in conjunction with SNMPv1 or SNMPv2. In addition, RFC 2271 describes an architecture within which all current and future versions of SNMP fit in SNMPv3 security model.

SNMP operates over User Datagram Protocol (UDP) of TCP/IP protocol suite, OSI connectionless Network Service (CLNS), AppleTalk Datagram-Delivery Protocol (DDP) and Novell Internet Packet Exchange (IPX). Management information is exchanged between a manager and an agent in the form of SNMP messages. The payload of SNMP message is either SNMPv1-PDU or SNMPv2-PDU. Security-related processing occurs at the message level. Figure 2.12 describes the differences between the message format in SNMP version 1, 2 and 3.

A PDU indicates a specific type of protocol operation and a list of variable bindings related to that operation. Generally, SNMP has seven protocol operations defined in SNMPv1 and SNMPv2. These operations are:

- get: used by a manager to retrieve specific information from an agent's MIB.
- get-next: used by a manager to retrieve an entire set of related information from an agent's MIB.
- get-bulk: used by a manager to retrieve a large amount of information from the agent's MIB without issuing multiple get requests. get-bulk operation was introduced in SN-

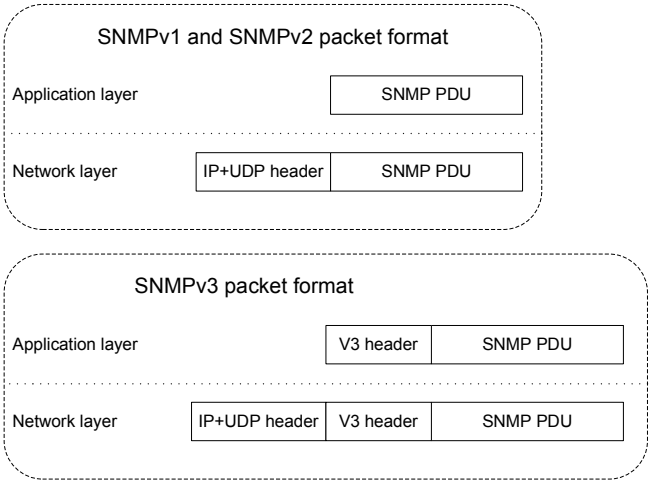


Figure 2.12: SNMP message format

MPv2.

- get-response: used by an agent to reply to get, get-next, get-bulk, and set requests.
- set: used by a manager to set a value in an agent's MIB.
- trap: used by an agent to notify a manager that some event has occurred. Traps messages are sent unsolicited. Also, the manager will not reply to the received SNMP-PDU.
- inform: used by a manager to notify another manager of specific condition or event. This operation was introduced by SNMPv2

Similar to CMIP protocol, SNMP-PDUs are constructed using ASN.1 encoding scheme.

2.4.3 Network Configuration Protocol

The NETwork CONFiguration protocol (NETCONF) is an IETF network management protocol initially defined in RFC 4741 and revised in RFC 6241. It is considered a major step towards an automated XML-based network management system since it provides standard mechanisms to install, manipulate, and delete the configuration of network devices [100]. The

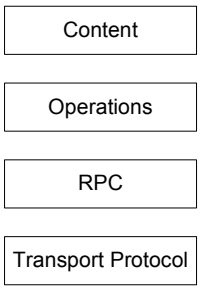


Figure 2.13: NETCONF's conceptual layers

standard uses XML based data encoding for the configuration data as well as the protocol messages. The protocol operations are transmitted using a simple Remote Procedure Call (RPC) mechanism on top of a suitable transport layer that provides a reliable, persistent connection between a manager and an agent.

NETCONF is conceptually divided into four layers as illustrated in Figure 2.13. The following is a description for each layer.

2.4.3.1 Transport Protocol Layer

The transport protocol provides a connection-oriented, persistent connection between NETCONF peers. The NETCONF connections *must* support authentication, data integrity and confidentiality. The mandatory transport protocol for NETCONF is the Secure SHell transport layer protocol (SSH) and the details for implementing this transport mapping are defined in RFC 6242. IETF has defined additional transport mappings. RFC 5539 defines mapping to the Transport Layer Security (TLS), RFC 4743 defines mapping to the Simple Object Access Protocol (SOAP), and RFC 4744 defines mapping to Blocks Extensible Exchange Protocol (BEEP). The Network Configuration workgroup in IETF is currently planning to move RFC 4743 and RFC 4744 to historic since there are very little implementations to support NETCONF over SOAP or NETCONF over BEEP.

2.4.3.2 RPC Layer

RPC layer describes in detail the format of NETCONF messages. A NETCONF request uses the <rpc> element to encapsulate a NETCONF operation. A NETCONF response uses the <rpc-reply> element to encapsulate the reply message. <rpc-error> is sent as part of <rpc-reply> message to indicate an error occurs during the processing of NETCONF request message. The error message may include further elements to provide detailed description of the error.

2.4.3.3 Operations Layer

NETCONF standard has defined a set of pre-defined operations to be used by *a manager* to manage and control managed devices. In addition, the standard allows *user-defined* operations to be included. In this case, a managed device must advertise these non-standard operations as part of the device capabilities. All operations defined in the current version of NETCONF are used by a manager.

NETCONF protocol distinguishes between two classes of management information: configuration data and state data. Configuration data is the set of variables that can be modified to configure a managed device. State data is the set of values that can be only read such as status information and collected statistics. In addition, NETCONF distinguishes between three repositories on a managed device: running, candidate and startup. Running repository stores the current active configuration data. Candidate repository stores the standby configuration. Startup repository stores the initial configuration of a device.

The base operations defined by NETCONF are:

- get: retrieve all or part of the current running configuration (running repository).
- get-config: retrieve all or part of a specified repository such as running or candidate.
- edit-config: create or modify all or part of a specified repository based on a set of attribute operations. NETCONF defines the following attribute operations: merge,

replace, create, and delete.

- copy-config: copy the entire configuration data from a source repository to a target repository.
- delete-config: delete the entire configuration data from a specified repository.
- lock: lock a given repository. This operation allows a manager to lock a configuration repository so that no other managers can perform updates on the same configuration repository.
- unlock: unlock a given repository.
- close-session: close an existing NETCONF session. Before a manager sends NETCONF operation, he/she establishes a session be sending HELLO. Sessions are identified by session id's. A session will be kept open until the manager close or kill the session.
- kill-session: kill an existing NETCONF session.

2.4.3.4 Content Layer

A new data modeling language called YANG has been developed specifically for NETCONF protocol. YANG is standardized and published in RFC 6020. It is not an object-oriented language but rather a tree-structured language. In other words, the management information is structured as an inverted tree such that the leaves constitute the configuration and state data.

In YANG, Management information is partitioned into modules where each module contains one or more tree containers. A node in the tree may represent a simple data type such as integer or a complex data type such as list or union. YANG has strong support for semantic validation than other data model languages (such as SMI). In addition, a YANG module can augment a tree in another module. This makes YANG very flexible for re-usability.

The advantages of using YANG for data definition include [87]:

- It is simple, easy to learn, and easy to read and understand.
- It is a domain specific language designed specifically for network management.
- It is flexible and modular. Existing modules can be augmented in a controlled manner.

2.4.4 Discussion and Critique

Although the CMIS/CMIP protocol suite has the capability of performing many management tasks, there are two serious problems associated with the protocol suite. First, there is a large amount of overhead to send/receive CMIS request/response. Second, CMIS/CMIP lacks industry support. It requires full implementation of OSI protocol stack. As a result, implementing CMIS/CMIP protocol is complex and costly. Moreover, network devices may not have enough processing power or memory space to support full OSI protocol stack.

SNMP protocol has been widely accepted by both equipment vendors and network management systems. Even though SNMP is a lightweight protocol and provides operation to configure network devices, it is only limited to collect statistics and status information from network devices. It is rarely used for configuration purposes. There are several reasons for this deficiency. Here, we mention the important ones:

1. SNMP protocol is simple, leaving the onus of manipulating configuration data on the management application. For this reason, tool development based on SNMP is expensive [76].
2. SNMP protocol stack has limited operational commands which are inadequate for large heterogeneous networks [76].
3. SET requests are sent independently. This may cause a serious network problem if a manager sent several SET requests to configure a particular device and one request is failed.

4. SET request may contain a list of variable bindings. If one variable binding is not valid, the whole SET operation will not be accepted.

5. SNMP does not provide any mechanism to undo recent changes in the device configuration.

6. SNMP does not provide synchronization among multiple network devices. If a manager sends SET request to a group of devices (to have similar configuration), some of them can succeed and others can fail.

7. SNMP does not employ the standard security mechanism. Instead, the security is self-contained within the protocol itself, which makes SNMP credentials and key management complex and difficult to integrate with other existing credential and key management systems.

NETCONF protocol has been developed to overcome the shortcoming of SNMP. One of the major advantages of NETCONF over SNMP is how the protocol works when manipulating a group of semantically related configuration data. Whereas SNMP modifies the value of a single parameter at a time, NETCONF modifies all or selected parameters on a single primitive operation. Another advantage of NETCONF is that it allows configuration to occur in a transactional manner. NETCONF takes into account when some of network devices successfully uploaded the configuration, but others failed to upload the configuration. NETCONF allows a managed device to rollback to a known-state configuration. This is because NETCONF defines transactional model that synchronize, validate, and commit device configuration within an entire network deployment.

Among the set of configuration standards described above, the most promising protocol is NETCONF, which is expected to be widely accepted by many network vendors. Major vendors of networking equipment are already started to implement the NETCONF standards (version 1.0 and version 1.1) in their production. There is no standard framework for NETCONF, but so far the framework consists of NETCONF protocol and the data modeling

language: YANG. The framework focuses primarily on the interaction pattern between a manager and an agent, and YANG language provides the uniformity of data representation. However, the framework cannot establish a bridge between high-level service configuration requirements and low-level configuration data to support network-wide configuration. Our contribution in this dissertation is to build such a bridge by defining a semantic model that supports network-wide configuration.

2.5 Current approaches to network Configuration

Network configuration management has been evolved since commercial networks first appeared. This section focuses on the protocol used to communicate with network devices in order to access configuration data.

2.5.1 Manual configuration

In manual configuration, network administrators use Command-Line Interface (CLI) to manage their networks. They use SSH protocol, TELNET protocol or terminal servers to communicate to network devices [100]. Manual configuration is only feasible for small-sized networks, but can be utilized for large networks in which few changes are expected over time. The main advantage of CLI is that network devices are closely monitored during each step of configuration. However, there are several disadvantages on using CLI. First, network administrators can easily commit errors during configuration process. Second, in multi-vendor networks, network administrators must remember all syntaxes and sequences to configure network services. This becomes specifically tedious work when the network supports multiple and complex services. Finally, CLI is not scalable for large-sized networks.

2.5.2 Script-based and template-based configuration

Script-based approach is considered the first step towards automation. In script-based configuration, a sequence of commands is programmed in a script file, when executed it generates a device-native configuration file (or commands) that can be directly uploaded to the device. This approach is especially useful for automating a repetitive management task. The script files are usually written using hybrid language; high-level language such as Unix shell, Perl, Python or domain-specific language and a low-level language which describes the actual CLI commands that an operator performs when configuring a network service or device.

Over the years, researchers have invested considerable efforts to improve script-based approach. Here, we classify script-based approaches into three categories: customized script-based approach, controlled script-based approach, and structured script-based approach.

In customized script-based approach [75], CLI commands or configuration files are encoded into modules or templates with placeholders for some key values instead of the actual values. When a script file is executed, the placeholders are replaced with the values provided as arguments. The main weakness of this approach is that CLI's commands are sent blindly. As a result, if a problem arises or an error occurs, continuing to send commands may not have the intended effect.

In controlled script-based approach [10, 12, 69], the flow of execution is controlled based on the execution behavior. The script language allows a manager to provide postconditions based on the response it receives to handle unusual conditions.

Structured scripting (or template) is an enhancement of controlled scripting that allows one to create scripts that are reusable on a larger network by providing a framework that assures coordination between network devices that support a specific network service.

The work in [26], which has developed a management system called PRESTO to manage large-scale networks, is one example of structured scripting. PRESTO generates device-native configuration files based on a set of templates called configlets. Configlets are written using a hybrid script language. The low-level language describes the actual commands that

an operator performs when configuring a network device, but without specifying configuration values. The high-level language is used to extract the necessary information from external database to determine which devices involved in service configuration, and to provide Configlets with the necessary configuration properties to produce complete configuration file.

It is quite obvious that Configlet is device-specific template since the actual configuration language is written using the device-native language. The work is suitable if the underlying devices are homogeneous. However, the system becomes very complex for multi-vendor networks since we need multiple Configlets for a single service.

Similar to PRESTO management system is NCG [68]. NCG is a management system developed by the network operator community in North America. The system is still under beta version. However, the idea of this system is quite similar to our idea on how to reduce the network configuration complexity. NCG needs two inputs: network description and NCG-based templates for the various configuration files of various devices. It generates, as an output, the actual configuration for each device to be installed. Thus, NCG requires manual pushing the configuration to network devices. AutoConf seamlessly integrates the generation of configuration and pushing it to network devices using NETCONF protocol.

2.5.3 Vendor-neutral Configuration

To resolve the issue of script-based approach specially in heterogeneous environment, management system must communicate with the underlying devices using vendor-neutral language.

SNMP-based configuration is one solution that provides vendor-neutral configuration [72, 67]. Due to the limitation of SNMP, many industrial tools, such as [61, 77] combine SNMP-based configuration with script-based configuration.

HTTP-based approach uses HyperText Transfer Protocol (HTTP) to transfer management information between agents and managers. In this case, agents (which are usually

referred as web-based agents) must have HTTP-server embedded in order to support HTTP-based configuration. Managers are simply web browsers.

The web-based agents may send static web pages to the managers or dynamic web pages, both encoded in HyperText Markup Language (HTML) [64]. Java applets and Servlets are also common methods of interactions in which HTTP is used to communicate between the manager and the web-based agent [9, 62].

A number of vendors have been working on XML-based management for several years. Juniper Networks developed Junos XML API for the Junos network operating system [51]. This API gives management applications full access to the agent's management information using Junos XML management protocol [52], which was formally known as JUNOScript. In addition to Junos XML framework, Juniper networks as well as Cisco started to adopt NETCONF protocol in their devices.

Many academic research projects have been proposed for XML–based network management systems. The work in [58] developed a software system called *Netopeer* to configure IP routers. Ju et al proposes an XML-based management architecture that is based on XML/HTTP as its management protocol [50]. The work in [63, 99, 21] focused on the translation of SNMP MIB modules into XML document. Other work [30, 5] focused on implementing SNMP/XML gateway.

2.5.4 Declarative-based Configuration

The increasing complexity along with administrator errors points towards an inevitable need to automate network configuration management. To handle rapidly growing complexity and to enable further growth, many approaches adopt the use of high–level programming language to describe the network behaviors. The main objective is to automate network management and reduce human involvement.

The literature comprises several works on providing automation in network configuration management. In addition, plethora of research work exists on autonomic computing

concept which provides autonomic computing for system management [82, 49]. Here, we only summarize the work related to automate configuration management.

SmartFrog [32] is framework for service configuration, documentation, deployment, and life-cycle management. The basic idea of SmartFrog framework is to visualize services as set of components. The component model enforces life-cycle management by transitioning components into five states: installed, initiated, started, terminated and failed. The framework comprises of an object-oriented language that supports encapsulation and inheritance. The language allows customized composition of service configuration by support post- and pre-conditions. The language enables static and dynamic bindings between components to support different ways of connecting components at deployment time. In addition, it has its own data model specification.

The work of Narain [66] proposed a solution to automate network configuration management tasks by formalizing high-level requirements using first-order predicate logic. The basic idea is to describe the network logically. Then, a requirement solver, which is basically a Satisfiability (SAT) solver, takes the description and tries to find a set of values that satisfy the logic. The work uses Alloy system as "requirement solver" system.

The network specification is written using the Alloy language, and it consists of three parts: components declarations which follow object-oriented paradigm, a set of predicate specifications (requirements), and model parameters. Alloy takes as input the network specification and produces components configurations satisfying those requirements.

The work is suitable for network design problems where it provides high-level description of network configuration. There are two major limitations in this work. First, the resulted configuration is described in a high-level language that requires an additional tool to translate the high-level language into device configuration. Second, the network specification will be too complex for large-scale networks, and network administrators may encounter difficulty to write efficient requirements. As a result, the SAT solver may not be able to produce an output at all.

2.5.5 Policy-based approach

Policy-based management (PBM) has become a promising solution for managing networked systems. The main motivation of PBM is to reduce the human intervention by providing dynamic adaptability of behavior by reconfiguration and addition of new policies without harming network operation [14]. This implies that PBM system should (i) transform management requirements to syntactical and verifiable rules governing the function and status of the network, (ii) transform such policy rules to device-native configuration, and (iii) enforce these configurations to managed devices.

One of the first architecture for self-managed networks introduced in literature called NESTOR [98]. NESTOR is organized in a four-layer architecture. The first and second layers (the bottom layers) emphasize the role of a uniform object-relationship model of network resources, in order to allow any kind of manager (human or software) to configure and control the network behavior. The network resources are expressed by using Resource Definition Language (RDL). RDL is an object-oriented interface language that supports the specification of resources as objects and their relationships. The top layers emphasize the role of uniform traditional interactions with the underlying resources. This is achieved by defining a shared object repository that unifies transactions and constraints that can be imposed to prevent known configuration inconsistencies. A language called Constraint Definition Language (CDL) is used to express the modeler constraints.

The IETF started its efforts by describing the architecture of PBM, which consists of Policy Decision Points (PDP), Policy Enforcement Point (PEP), Policy repository and Policy management tool defined in RFC 3198. Policies are defined through Policy Management Tools and those policies are stored in Policy Repository. PDP is responsible to take decision based on policies stored in Policy repository. PEP is responsible to enforce the decisions on managed devices. PDP and PEP are communicated through a protocol called Common Open Policy Service (COPS), which is defined and published in [4]. In PBM, policy information is represented through the Policy Core Information Model (PCIM), which is an

extension to DMTF's CIM model, and PCIM was produced jointly by DMTF and IETF (see [65]).

Sloman and Lupu [78] provide a comprehensive, but slightly outdated, description of management policy specification. One of the key points they raised is that there is a marked separation between policy languages that are applied to specific domains. The authors along with others have developed a policy language called Ponder as part of ongoing work in Imperial College, London [24]. The authors distinguish six types of policies: positive authorization, negative authorization, refrain, positive delegation, negative delegation and obligation. The Ponder language is declarative object-oriented language that supports these policy types. While these policy types allow for a rich policy set for management, it has some shortcomings. Refrain, positive authorization and negative authorization policies have no event clause, which can cause efficiency and predictability problems.

The work in [83] proposed a tool called Focale that uses PBM to automate network management. It uses ontologies to model the managed resources and heterogeneous data by mapping their facts into a common vocabulary. Focale uses a mid-level model called Model-Based Transaction Layer to convert high-level policies into device-native configuration data. The developers of Focale have introduced the term "Policy Continuum" to indicate that a policy may be viewed on different constituencies. This means that a policy can be placed on different abstraction levels.

2.5.6 Separating Data and Control planes approaches

Several research works have addressed the network management complexity by raising two key points: (1) separating the functionality of the data plane and control plane and (2) programmability instead of configuration [73, 56]. This has led to a new paradigm named software defined networking (SDN).

The grandfather of SDN is 4D project [34], which has addressed the need for separating between control and data planes as well as centralized administrative domain. 4D

architecture actually proposed four planes: decision plane, dissemination plane, discovery plane, and data plane. The decision plane determines the overall network behavior based on network-wide view collected from the underline devices. The data plane performs basic packet processing functions such as forwarding, filtering, etc. The dissemination plane serves as a communication mechanism between the decision plane and data plane. The discovery plane is responsible for discovering the underlying physical devices. The concept of 4D concept has been implemented in Tesseract system [97]. The system has been designed to provide a platform with pluggable programmable modules.

CONMan [8] architecture defines a set of abstract modules that capture data or control plane functions. Ethane [16], NOX [35], and Maestro [97], which are all inspired by 4D project, are focusing on network flow access control management. Ethane has been deployed at Stanford's Computer Science Department, which gave the developers a real evaluation to the concept of 4D.

The success of Ethane has led to OpenFlow, an open standard for programmable flow-based switch developed by Open Networking Foundation [71]. An OpenFlow-capable switch processes packets according to a flow table. The flow table is a set of matching rules over packet headers such that each rule has an action to be taken. A "logically" centralized controller is responsible to control the flow tables in OpenFlow capable switches using a set of pluggable, programmable modules.

Currently, SDN paradigm is a popular programmable architecture. It allows administrators to program their network and to deploy network services via programmability instead of configuration. on the other hand, our work is focusing on network configuration management.

2.5.7 Discussion and Critique

We presented various techniques to automate network configuration management. Majority of these techniques rely on a high-level language where the language has its own data type

definitions. This may create a conflict between the data type of a specific configuration parameter defined in the language and the data type defined at the device level. Moreover, if network devices are managed via standard protocol like SNMP, the overall management architecture will end up with two different data models: a data model at higher level (part of high-level language) and a data model provided by the standard protocol (such as YANG or SMI). Our approach provides automation by using programming and policy based approach; however, the language is designed to orchestrate with the data modeling language. Thus, instead of having a single complex model to translate high level policies into device native language (as in FOCALE and SmartFrog), our proposed framework divides management complexity into a set of layers where the lower layers are based on a standard architecture which is the NETCONF framework.

We mentioned various approaches that define the interaction protocol between a manager and an agent in order to manage configuration data. A manager can access the configuration data either directly or indirectly. A direct access is achieved by using CLI through manual configuration or script-based configuration. These approaches have the advantage of efficiency since they do not require a translator (to translate from high-level language to device-native language). The disadvantage is that each device may have its own language or CLI. Using manual configuration and script-based configuration in a heterogeneous network are impractical.

Indirect access is achieved by having a high-level language and a management protocol. It requires a translator application (agent application) to translate high-level language to device-native language. The purpose of having a high level language is to have a unified view of related configuration data regardless of the device manufacturer. SNMP-based approach is considered the most dominant approach to access configuration data indirectly due to its simplicity and low cost. Before SNMP-based approach, the object-based approach existed but was not widely accepted due to the extra overhead when transferring managed objects.

With advent of Internet, HTTP-based approach has been introduced. HTTP-based

configuration has the same advantage as in SNMP-based approach. However, it has the same disadvantages as in the script-based approach.

XML-based approach is considered the most attractive technique to access configuration data due to the powerful features of XML technology. The work in this dissertation uses XML-based approach since we rely on NETCONF protocol to convey configuration data. As reported by [100], the downside of XML is overhead when handling with a single value of configuration data.

Recent approaches to automating network configuration management are influenced from software engineering principles. The main shortcoming in these approaches is the device life cycle, which is based on an isolated computer system life cycle [89]. However, our approach concerns about the life cycle of a whole network in order to achieve network-wide configuration.

Our work is not much different from the concept of SDN even though our work focuses on traditional network management. OpenFlow-enabled network can still benefit from our work in two areas: the bootstrapping of the network and policy manipulation. Based on [71], OpenFlow-enabled network is relying on NETCONF protocol as a main protocol to configure switches and controllers during the bootstrapping. Moreover, the work in this dissertation provides a solution to manipulate and verify flow tables.

2.6 Configuration Verification Approaches

In the past few years, many researchers have attempted to address various challenges in network configuration management, and most of which have focused on detecting configuration conflicts within certain devices. The work in [36, 101, 33] focused on firewall devices. The work in [29] [90] focused on detecting routing misconfiguration.

Static, end-to-end formal analysis was first introduced by [94] and later has been extended and implemented by [55]. Our work is similar to their work with some differences. Our

approach models a network as a graph over links, while [94] and [55] model a network over devices. There are two advantages using our graph model. First, it allows us to provide fine-grained analysis since we encode the effect of each device on its incident links. Second, their algorithm runs in $O(|V|^3)$ time ignoring the cost of set operations, where V is the number of vertices (devices) in a graph. Our algorithm in worst case runs in $O(2 \times |L|^2)$ time, where L is the number of links in a network. Moreover, in [55], the paper assumes that any packet passing a NAT device will be translated but the translation function is not well defined.

Global verification has also been discussed in [1]. The authors have used model checking to achieve end-to-end analysis. The main disadvantage is that the model formalization uses huge number of bits (591 bits). In addition, using BDD representation for model checking has the limitation of the state-explosion problem, particularly when used to verify large networks.

2.7 Summary

This chapter started with a brief introduction to the methodologies and models that will be used in this dissertation. Then, we presented the major contribution of standard bodies in network configuration management and the major network configuration protocols. We analyzed the prior work for network configuration management by dividing it into three dimensions. The first dimension concerns on how to access the configuration data. We presented several approaches starting from manual configuration up to XML-based configuration. The second dimension concerns on configuration management scalability. We presented several prior projects along with their limitations. The third dimension concerns on automating network configuration. We presented different approaches to achieving automation using policy-based techniques. We concluded this chapter by reviewing recent research works in configuration verification.

Chapter 3

Configuration Semantic Model

Management systems require a detailed description of managed devices and their associated services to automate network configuration. This chapter provides an overview of required functionalities of an automated system. Then we describe the main components of our proposed system: AutoConf. Moreover, we introduce an information model called Configuration Semantic Model (CSM) along with its associated language called Structured Configuration Language (SCL). Then we show how CSM and SCL simplify configuration process by abstracting away the underlying complexity of configuration process.

3.1 Overview

Given the complexities and challenges of network configuration, an effective configuration framework does not only define a model to unify all data but also provide a global view of all knowledge needed to support automated network management.

Recent approaches to automating network configuration management are influenced from software engineering principles. The main shortcoming in these approaches is that they rely on the concept of device life cycle, which is based on an isolated computer system life cycle [89]. The purpose of studying device's life cycle is to ensure a flawless operation of

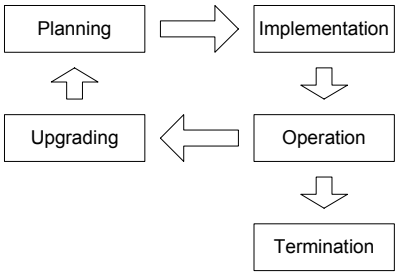


Figure 3.1: Life cycle of a networked device

networked system. Based on software engineering, the life cycle comprises of four stages: planning, implementation, operation, upgrade and termination as shown in Figure 3.1.

However, a healthy network has a set of services (or functions) operating in a harmonic way. A network service is not only associated with a single device. For example, OSPF routing protocol is meaningless with a single network device. Furthermore, a network service, when operates, should not *harm* other network services. Thus, a life cycle, which ensures flawless operation of a networked system, must capture the network as a whole not as an individual device or service.

Our envision for an efficient automated network configuration is based on the following features:

- The automated system should support standard technologies. This will guarantee the ability to manage the same network services independently of the underlying network device's hardware or operating system.

- The system should scale well, so distribution of management activities on the local management domain has to be attained.

- The system should be able to automatically configure and continuously validate all relevant network services in the management domain. The configuration is accomplished based on a set of policies that define administrator's requirements.

- An independent high-level specification language should be adopted to configure all

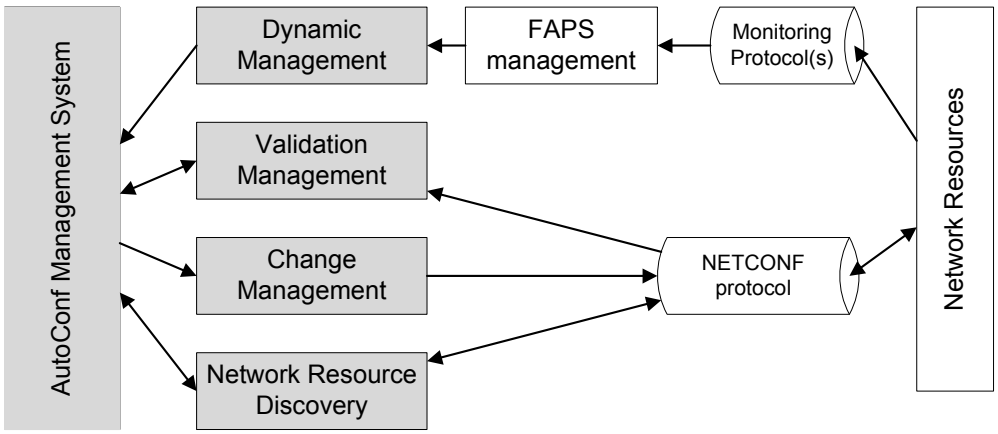


Figure 3.2: AutoConf management system

network services, network devices and the management system itself. This language forms a unified interface between a network administrator and the automated system that allows administrators to access all underlying devices and to define requirement specifications.

3.2 The framework

The problem of network configuration management is divided into three parts. The first part explores the configuration change management. The focus of this part is to improve configuration management by organizing management functions semantically and formalizing configuration specifications. The second part focuses on configuration validation management. This part explores the theoretical approach to validate network configuration as well as network behavior. The third part concerns on dynamic network configuration, which is responsible for responding to any change in network state. The response should take into consideration the high level requirements stated by network administrators and the current network state.

Figure 3.2 shows the overall components of our proposed automated management system called AutoConf. AutoConf system relies on NETCONF protocol to query or change the configuration of network resources. Network Resource Discovery uses NETCONF and

YANG to define the set of resources that need to be managed and controlled within the domain environment. Once the resources are defined, AutoConf system goes through two cycles. Both cycles start at the change management. The change management is either triggered automatically or manually, which adds, deletes, and updates configuration data of network resources. The validation management will automatically be triggered to read operational data and report the result back to the automated system. This will constitute the first cycle. The Fault, Accounting, Performance and Security (FAPS) management will continuously monitor the network resources. Any deviation from normal state will be reported to the dynamic management. The dynamic management analyzes the report and informs its decision that should be taken to correct the situation to AutoConf system. This will constitute the second cycle. The automated system invokes the change management to enforce the new change automatically and hence the first cycle will be performed.

The aforementioned parts are not isolated but rather orchestrated by a common framework as shown in Figure 3.3. The framework assumes that managed resources are running NETCONF servers (`netconfd`). `Netconfd` acts as an agent and translates NETCONF messages into device-native management information and vice versa. If a network device does not support NETCONF, a proxy NETCONF server will be used.

The framework supports distributed management framework with a centralized database management. Remote managers write SCL commands to manage and control network services and resources. SCL engine, which is part of AutoConf engines, translates SCL commands and generates NETCONF messages to be sent out via NETCONF protocol to `netconfd` servers. SCL engine and Netconfd servers must follow YANG specifications to exchange management information[1]. In addition to SCL commands, Remote managers describe their intentions or requirements by using the CSM, which covers the required information to automate configuration management. In the following sections, we describe the semantic model and the SCL specification.

[1]The YANG language is explained in Appendix A

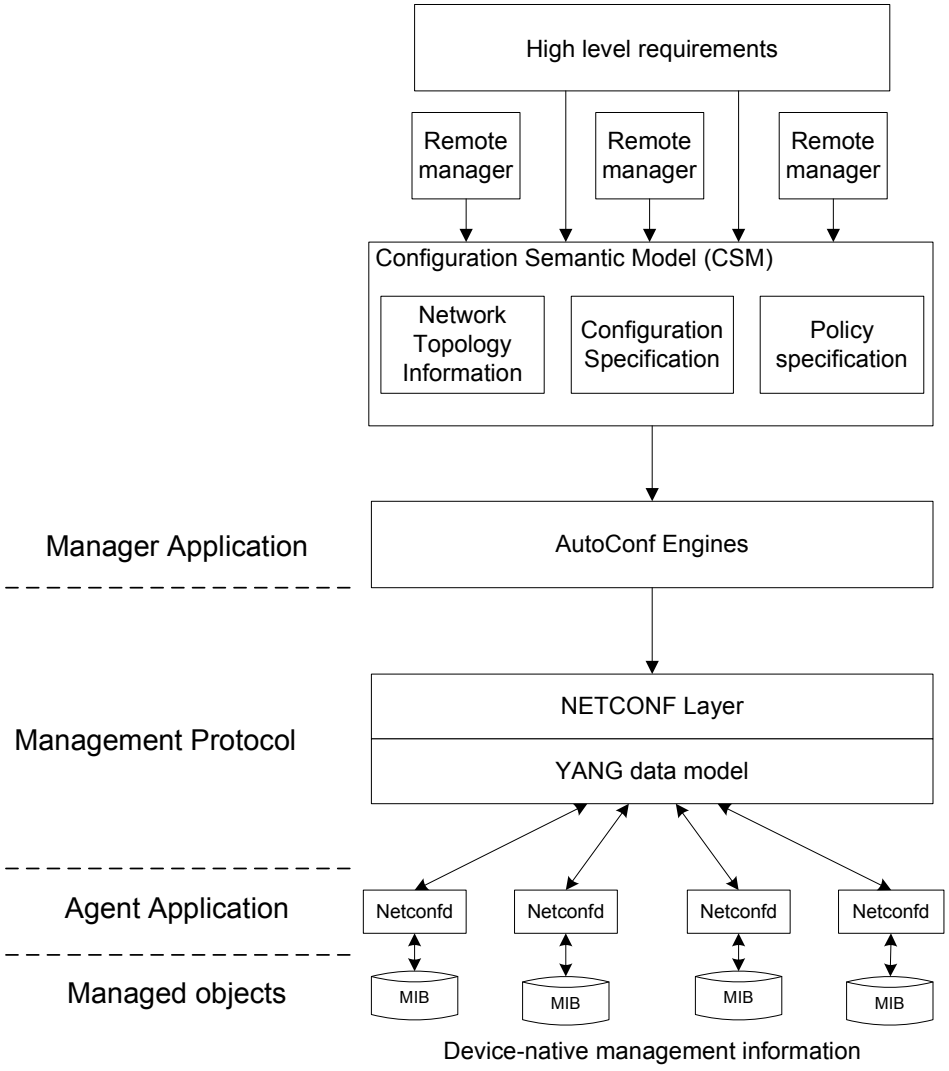


Figure 3.3: AutoConf framework

3.3 Configuration Semantic Model Concepts

To improve the configuration process and change management, a middle level is required to link the dependencies between configuration information and to allow network administrators to enforce certain policy and consistency rules on configuration data that resides on different network devices. In other words, the main purpose of the semantic model is to engineer and manage the high-level knowledge about the network, management functions, network services and the underlying devices. We call this semantic layer Configuration Semantic Model (CSM).

The main objectives of having configuration semantic model are two-fold. The first objective is to interlink configuration semantics to establish network-wide configuration. The second objective is that CSM abstracts away the details of individual configuration data and instead works on a unified abstraction, which fundamentally establish a common vocabulary between the Automated System and network administrators.

Our methodology to construct CSM model is to use knowledge management engineering as described in [53]. CSM model has a set of *concepts*. A concept, which represents an ontology in the domain of network management, is characterized by a set of attributes and possible classification. Thus, concepts are organized in hierarchical format and stored in a centralized database such that multiple managers can access the same database.

Generally, CSM covers four types of information: topology specifications, configuration specifications, policy specifications and status specifications. The following sections define the set of CSM concepts (or ontologies) that are used to describe each information.

3.3.1 Topology Specification

Network topology is modeled by using the following concepts: `device`, `service`, `interface`, `link`, `data`, `yang`, and `repo`. The following is a description for each one:

Device: This concept provides a logical representation of any network element that needs to be controlled and managed. It is not necessarily representing a physical device; a device can be a logical element such as an autonomous system or a management domain. A device is characterized by a name, a parent device, and a group. A device may have one or more children devices. In this case, the device represents a domain. A domain device semantically links several devices to form a logical domain. Configuring these devices can be accomplished by configuring the domain device. For example, let us consider a network with three routers that run OSPF routing protocol. Instead of configuring each device individually, we may create a domain device and configure that device only.

Interface: This concept represents an abstraction of an interface. An interface can be a logical interface or a physical interface. It is a part of a device resource. An interface is characterized by a name, a device name, an index number, and info. The attribute info is a list of properties for describing the interface.

Link: Link is an abstraction for any type of connectivity between two adjacent devices. CSM allows to build a hierarchy of connectivity between two adjacent devices. For example, router A is physically connected to router B using 1000Base-T Ethernet cable. The routing table of router A indicates that router B can be its next hop. Thus, router A and router B are logically connected. However, the logical connectivity cannot be exist unless there is a physical connectivity between the two routers. To express this scenario, CSM allows us to define a link where its existence relies on the existence of its parent link. `link` is characterized by a class, ports, and a parent link. If a link has no parent, then parent link is `undefined`. Ports is a list of two tuples such that each tuple represents an end point. For example, {link, fa, undefined, [{r1, 1}, {r2, 1}]}.

Service: The concept of service abstracts any activity (at any OSI layer) that needs to be managed. A service is characterized by a name and a group of activities. For example, OSPF is a service that performs *routing* activity.

Data: Each service is associated with one or more data modules that determine its behavior. One reason of having multiple data modules for a single service is to provide multiple views for the same network service. For example, it is possible that a network accommodates two routers from different vendors. Both routers support OSPF protocol; however, each has its own data representation. As such, the service OSPF has two data modules.

A data is characterized by a service name, data type, and module name. Data type is the data model used such as YANG or SNMP SMI.

Yang: If a service has a data module of type YANG, there will be a concept of type yang. A yang concept is characterized by module name, prefix, namespace, list of container names, and YIN root. YIN is the equivalent representation of YANG module in XML format.

Repo: A device may have several data repositories. When a manager needs to configure a network device, it accesses a specific data repository of that device and starts modifying its data. A repo is characterized by a device name, data module type, data module name, data module info, and options.

To illustrate the relationship between the above concepts, let us consider a border router called RTR01 in area one that supports multiple routing protocols such as RIP, OSPF and BGP. We describe the topology as follows. The network devices are `area-one` and `rtr01` where `area-one` is the parent device of `rtr01`. We classify `rtr01` as `router` and `border_router`. The network services are rip, ospf, and bgp; all doing routing activity. Assuming the network supports NETCONF and YANG. Each service is associated with a data module of type YANG. `rtr01` supports the following repositories: ospf data module, rip data module, and bgp data module.

AutoConf system creates repositories automatically by navigating device capabilities. However, a network administrator must manually define services and data modules. The reason is to give more controls at the manager side what configurations are required. In other words, defining services and data modules specifies AutoConf capabilities. For instance, a router may support many intradomain routing protocols such as RIP, OSPF, IGRP, and ISIS. We may only tell AutoConf to consider OSPF and RIP when automating routing activity.

3.3.2 Configuration Specification

The CSM allows a domain expert to extend its model by introducing user–defined ontologies. These ontologies are intended to provide a unified view of the *current* network configuration.

Having a unified specification has the advantage of making configuration process easy to write and understand. For example, we can define a concept called `ospf_net` that contains network address, network prefix, area id, and a list of attached routers as shown below.

```
<ospf_net, "192.168.10.0", 24, 1, [rtr03]>,
<ospf_net, "192.168.20.0", 24, 2, [rtr02]>, and
<ospf_net, "10.1.100.0", 24, 0, [rtr01,rtr02,rtr03]>
```

3.3.3 State and Policy Specification

We will postpone the discussion of state and policy specifications until we reach Chapter 5 when we discuss the network automation subsystem.

3.3.4 Overall Organization

Thus, the overall view of the CSM will be as follows. To build a typical network, we define a *logical* device that represents the network environment. Under this device, network administrator has the option to segment management domain into multiple sub domains such that each sub domain has a domain device. Then, we define manually the set of services supported by the network and what YANG modules support each network service. Then, we define network devices either manually or dynamically via Resource Discovery Module. AutoConf queries each network device and generates automatically repo concepts for each device. Figure 3.4 shows the overall semantic hierarchy of a network.

The set of all concepts that belong to a particular management domain is called *Domain Knowledge Base (DKB)*.

3.4 Structured Configuration Language

We propose a high-level language to represent the CSM and to facilitate network services configuration management. The new language is called Structured Configuration Language

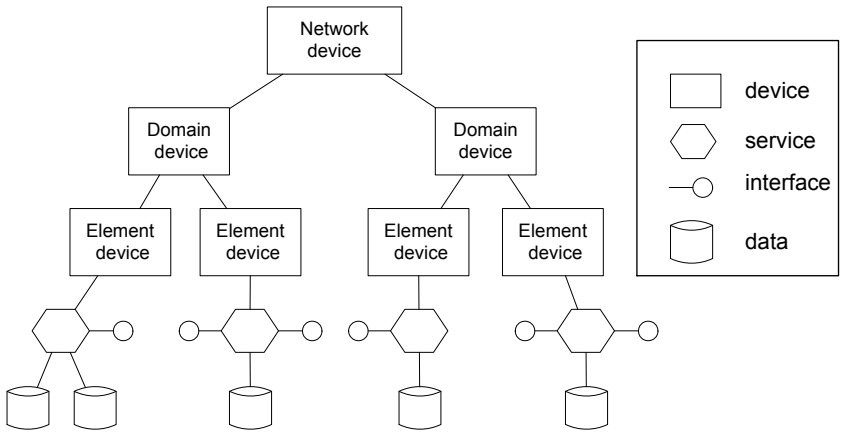


Figure 3.4: The hierarchical structure of Configuration Specification

(SCL). It consists of a set of instructions aimed to create, view, manipulate, and delete data stored in configuration repositories as well as to manipulate CSM concepts. The language has the following features:

- **Simple and easy to read**. The language contains small set of statements and rich set of useful functions. The syntax of SCL is very close to the syntax of YANG modeling language. Therefore, it would not be difficult for an administrator to read and write SCL code as well as YANG modules.

- **Conform to NETCONF framework**. Unlike other languages[2], SCL is a tree-structured language which makes it suitable for NETCONF protocol and YNAG language. The reader of SCL commands can see the high-level of configuration specifications while understanding how the operations will be encoded in NETCONF requests.

- **Aggregation**. A single SCL command can configure a group of networking elements by sending multiple NETCONF messages.

- **Atomicity**. One important feature of the SCL is that it supports an atomic statement which means SCL statement with atomic option enabled will either be executed com-

[2]Such as CIM Query language

pletely or not at all. SCL assumes that NETCONF servers support rollback capability in order to achieve atomicity.

For more details, the reader can refer to appendix B.

3.4.1 Improved Configuration Management

SCL statements that are responsible to manage network devices consist of a domain model followed by one or more configuration rules. The separation between domain model and configuration rules allows the manager to focus on service management regardless of the underlying network devices. A domain model provides the set of devices we should deal with. Configuration rules provide the actual configurations for managing a network service. Each rule handles certain data model version. The mapping between a data model version and a network device is achieved automatically by AutoConf.

AutoConf management system exchanges NETCONF HELLO message with each device in the network. Through these messages, AutoConf discovers the capabilities of each network device and what data model versions it supports. These capabilities are stored in KDB via *repository* concept. Therefore, when AutoConf processes SCL statement, it will consult device repositories to resolve the configuration rules.

The general syntax of SCL statements that manage network devices is:

```
domain : service_name [ constaint ]
    configuration rules
```

A domain can be a single device (specified by device name), a group of devices (specified as a list) or a parent device. A parent device is analogous to super class in object-oriented paradigm. The constraint is pertaining to domain model that provides a fine-grained selection of network devices. Let us illustrate it by using an example.

Figure 3.5 shows a network with a set of routers. The shaded rectangles represent the conceptual representation of these devices along with the network using CSM *device* concept.

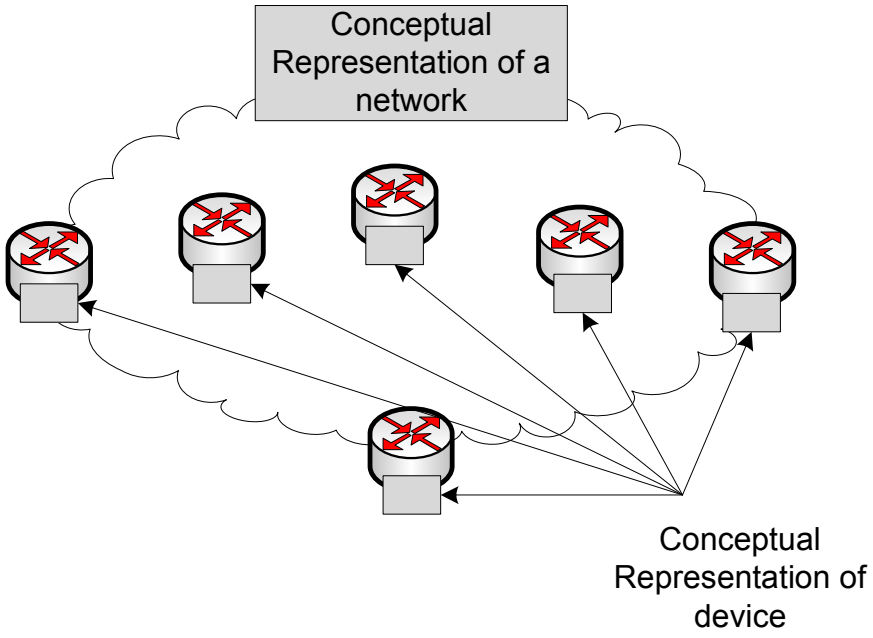


Figure 3.5: A network with a set of edge and core routers

As we mentioned before, CSM allows us to conceptually represent a network as a logical entity that encapsulates all network devices in the network. Here the network device acts as a parent device of all router devices.

If we need to enable OSPF configuration on all routers in the network, then our domain will be the network device itself. Configuring the network device is equivalent of configuring all devices in the network. If a network operator is requested to enable specific QoS, then he/she needs to perform some configurations at edge routers and core routers. If the target devices are all edge routers then the domain will be the network device with a constraint that devices should belong to edge router. Please refer to section 3.3 on how to define groups.

Configuration rule provides the actual configuration for a specific data model version. For example, if a network operator needs to enable network interfaces in routers, but there are different versions that describe network interface data model (e.g. YANG model developed from Cisco vs. YANG model from Juniper), then he/she should provide a configuration rule for each data model without concerning the underlying physical device. AutoConf selects the rule that matches the device capability automatically. Therefore, CSM and SCL

framework simplifies configuration process by shifting the focus from physical configuration management to service management.

In Chapter 7 we show how CSM configuration specifications abstract away the low level configurations.

3.5 Summary

Using configuration management language whose process is close to manual administration simply does not work in large and heterogeneous networks with different data representations for the network service. When enabling a network service in heterogeneous networks that involves multiple devices, administrators face subtle configuration process. Indeed, the subtle interactions between different versions of the same of network service can make the cost of management process excessively large. As a result, we developed a new framework to accommodate management activities and proposed a new information model called CSM to provide high level of network configuration process. To enable CSM, we designed a new language called SCL that significantly reduces the complexity of network configuration management.

Chapter 4

Configuration Verification

4.1 Overview

Modern networks are designed and deployed to satisfy a wide variety of competing goals related to different network requirements, such as security vs. availability, and performance vs. manageability. These high–level goals are realized through a complex chain of configuration commands which include service provisioning configurations along with thousands of access control rules from different policies such as packet filtering rules, routing policies, and packet transformations.

Due to various reasons, including security policy updating, new service provisioning, and system upgrading, network configuration needs be often revised accordingly, which makes the probability of misconfiguration unfortunately high. As we mentioned in Chapter 1, several surveys show that misconfiguration is the most critical threat to network operation. In addition, a local configuration change or network failure may even inadvertently result in a global impact on existing network services or policies. For example, when a network link goes down, the network may converge into a new topology that has not been envisioned by network administrators. This may indirectly cause illegitimate traffic bypass security protection or legitimate packets accidentally blocked. Thus, verifying network configuration

routinely based on dynamically updated (e.g., via SNMP trap) network topology is a highly desirable network service to enhance network reliability and manageability.

It is a significant challenge to verify in a timely fashion the configurations of a network system, which may consist of hundreds or thousands of different devices with possibly hundreds or thousands of configuration rules on each device. Network debugging tools such as *traceroute* or *ping* can test network reachability but cannot reveal the details of reachable packets. There is a growing consensus on the need of formal models and programming interfaces to conduct configuration verification in order to validate enforced network policies. As such, many researchers have proposed formal models of network security and reachability such as static analysis [94], firewall decision diagram [33] and model checking [1] as a solution to overcome the limitation of debugging tools.

However, the proposed solutions suffer from a serious limitation which always requires a complete construction of the entire model in order to answer queries for checking various service reachability and security polices. Enterprise network administrators and Internet service providers, in case of any topology change or network failure events, require a timely diagnosis to maintain their network integrity and service quality and to reduce potential revenue loss.

In this chapter, we divide the problem of configuration verification into two main categories: Consistency verification and Behavioral verification. Within each category, we further divide it into a set of scopes. We named these scopes *configuration verification levels*. Therefore, under a category, we analyze the verification problem by breaking it into a set of verification levels and propose a solution at that level.

4.2 Network Verification Levels

When we need to verify a network operation, we construct a set of *verification rules* such that one or more rules are pertaining to a specific requirement or administrator's intention. There

are different scopes (or levels) of network requirements. For example, one may specify the following two requirements: certain traffic should not pass through a specific intermediate device and there is a connectivity between two subnets. The first requirement is related to a single device while the second one is related to a group of devices. Moreover, some requirements should be specified to ensure the correct operation of a network. For examples, we may need to verify that dependent configuration parameters are consistent, or we may need to verify that for any two routers that are directly connected by a link, the two interfaces attached to the link have IP addresses that belong to the same subnet. In this dissertation, we propose the following levels to achieve network verification:

- *Data-level verification*, which is pertaining to the data uploaded to network devices,
- *Device-level verification*, which is pertaining to a network device,
- *Link-level verification*, which is pertaining to directly linked devices,
- *Service-level verification*, which is pertaining to a group of devices that are collaborating to achieve a specific network service, and
- *Network-level verification*, which is pertaining to some or all network device functionalities to achieve high-level requirements such as reachability, security, etc.

Since there are two types of data in any network: configuration data and state data, we distinguish two types of verification:

- *Consistency verification*, to check the consistency of configuration data at some specified levels
- *Behavior verification*, to ensure status information such as access control lists or routing tables on network devices are valid and do not conflict with high-level requirements.

4.3 Consistency Verification

Network configuration may involve several devices in order to enable a network service. For example, OSPF routing protocol requires all devices in a single network to enable OSPF process. Otherwise, OSPF will not operate successfully. We distinguish several levels of consistency verification: data–level, device–level, and service–level verifications. Data–level verification concerns about the correctness of the uploaded configuration data in general. For examples:

- Is an interface configured with a valid IP version 4 address?
- Given an interface name, does this name exist in the configured device?

Link–level verification concerns about the consistency of configuration data between two devices that share a common link. For example, the IP addresses of any two linked interface must be consistent. Device–level concerns about the consistency of configuration data that is related to a single device. One example at this level is to ensure that no two distinct interfaces of the same device are placed on the same subnet. Service–level verification concerns about the correctness of configuration data to enable a network service. The OSPF example given above demonstrates service–level verification. In this section, we discuss how to provide a consistency verification at data, device, link and service levels.

4.3.1 Data–level Verification

At data level, we rely on YANG data model since YANG provides an efficient mechanism to ensure the correctness of syntactic and semantic of configuration data. In addition, several parameters can be logically compared using `must` with XPath expressions. `must` statement is very useful when the existence or possible state of a parameter may depend on another parameter that exists somewhere else in the *same* configuration data module.

4.3.2 Device and Service-level verification

When configuring a network service, we need to ensure the state of a parameter is consistent with other states of the same parameter on other devices. For example, we need to ensure that the OSPF timers on one router is consistent with OSPF timers on other routers that provide OSPF service. To model this, let S be the set of states of a parameter on different devices. Then the set S is consistent if the following *verification rule* is true:

$$Q\ x \in S : F(x) \tag{4.1}$$

where F is a constraint over x, and Q is quantifier that can take values as tabulated in Table 4.1. For example, **all** $x : F(x)$ is true when each value in S satisfies $F(x)$, and **-1** $x : F(x)$ is true when at most one value of x satisfies $F(x)$.

Q	meaning
all	universal all
some	existential
no	no values
N	exactly N values
$+N$	at least N values
$-N$	at most N values

Table 4.1: Quantifier values

To construct a verification rule, we first need to specify the set S. In heterogeneous network, not all services are modelled using the same data model; each service might be modelled by using vendor-specific data schema. This means that the location of a configuration parameter in one device may differ from other devices.

One possible solution is to use XML transformation or XSLT (Externsible Stylesheet Language Transformations). XSLT is a set of rules that transforms an existing XML document to a new XML document, as shown in Figure 4.1. The rule's matching criteria in XSLT is an XPath expression. When there is a pattern matching, the rule's template form will be evaluated, and the result constitutes XSLT processor's output.

Writing XSLT for various devices to match vendor-independent schema could be a tedious job. On one hand, network operators must learn how to write XSLT documents. On another

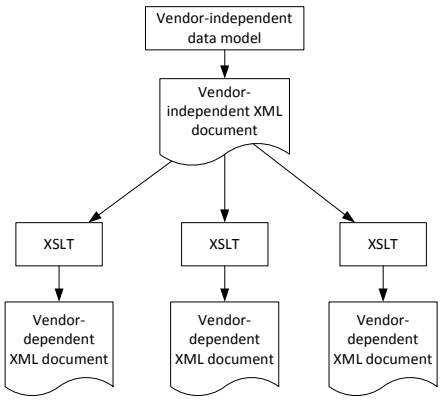


Figure 4.1: XSLT transforms XML documents to another XML documents

hand, they need to maintain these documents to reflect the latest versions of vendor-specific data models.

In this dissertation, we provide the same solution but without writing a complete XSLT document. In our approach, a matching rule is composed of two entries separated by ':'. The first entry is the module name and the second entry is the XPath expression. For example, the list below shows a set of matching rules that construct the set S:

```
/* matching rules */
standard: "/ospf/timers/update";
cisco_md: "/config/ospf/update-timer";
```

The construction is as follows. If a device supports standard data module in its repository, AutoConf sends NETCONF *get* request with XPath expression `"/ospf/timers/update"` to that device. If the device supports cisco data module in its repository, AutoConf sends NETCONF *get* request with XPath expression `"/config/ospf/updata-timer"` to that device.

NETCONF reply to GET request with XPath filtering has three forms. The first form is when XPath expression matches a single instance in the retrieved XML document. In other words, the configuration parameter has a single value. We call this form *content* form. The second form is when XPath expression matches multiple instances in the retrieved XML document. We call this form *list* form. The last form is when XPath expression matches no

instance. The data node of the retrieved XML document is empty. For example, the XPath expression `"/interface["eth0"]/address"` is expected to provide the IP address of eth0 interface (content form). However, the XPath expression `"/interface/address"` returns the IP addresses of all interfaces (list form).

4.3.3 Link-level verification

In link-level verification, the set S consists of a set of pairs (x_i, y_i) where x_i and y_i represents parameter values for two linked devices A and B, respectively. For example, the following statement:

```
verify link [r1, r2]:interface {
  content {
    standard: "/interface/name[" ++ #interface.name ++"]/address";
    cisco_md: "/interface/name/" ++ #interface.name ++"/ip-address";
  }
  assert all : subnet(X,24) == subnet(Y,24);
}
```

returns true if the IP addresses of the two interfaces sharing a common link have the same subnet address. The function subnet() needs two arguments: an IP address and network prefix. It returns the subnet address.

4.3.4 SCL Language Related to Consistency Verification

SCL supports consistency verification through `verify` construct. `verify` statement takes two arguments as in `manage` statement: device and service identifiers. Consider the following verification rule in SCL language:

```
verify *:ospf {
    content {
```

```
        /* matching rules */
        standard: "/ospf/timers/update";
        cisco_md: "/config/ospf/update-timer";
    }
    assert all : int(X) >= 25 and int(X) <= 45;
}
```

The above *verify* rule says that for each device that supports `ospf` service, the update timer should be between 25 and 45 seconds. AutoConf collects the information as follows. If the device supports `standard` module in its repository, use the XPath "/ospf/timers/update" to extract the correct parameter value. Otherwise, if it supports the vendor-specific `cisco_md` module, use the XPath "/config/ospf/update–timer". Otherwise display a warning message. `content` clause represents the set S while `assert` clause represents the consistency formula as expressed in 4.1. The function $int()$ is used to convert XML text to integer.

The following rule states that for each device, no non-equal interfaces are placed on the same subnet with subnet prefix 24:

```
verify *:interfaces {
  list {
    standard : "/interface/address";
  }
  assert all : distinct(subnet(X, 24)); // 24 is subnet prefix
}
```

The SCL engine understands that the variable X is a list. So, the function `subnet/2` returns another list that will be an argument for `distinct/1` function. This function, in turn, returns true if all elements in X are distinct.

4.3.4.1 High-order verification

Let

$$\begin{aligned} E_1 &::= Q_1\ x \in S_1 : F_1(x) \\ E_2 &::= Q_2\ x \in S_2 : F_2(x) \\ &\vdots \\ E_n &::= Q_n\ x \in S_n : F_n(x) \end{aligned}$$

be a set of verification rules. We wish to evaluate an expression that connects the above rules using AND or OR logical operators. To do that, let $S = \{E_1, E_2, ..., E_n\}$ and the constraint expression is expressed in Equation 4.1. Since each element of S is eventually a Boolean literal (true/false), the constraint expression can be reduced to $Q\ e \in S : e$ **is true**. There are three values of the quantifier Q that can be used here: **all**, **some**, and **no**. When the value of the quantifier Q is **all**, then **all** $e \in S : e$ **is true** is equivalent to $E_1 \wedge E_2 \wedge ... \wedge E_n$, when the value of quantifier Q is **some**, then **some** $e \in S : e$ **is true** is equivalent to $E_1 \vee E_2 \vee ... \vee E_n$, and when the value of quantifier Q is **no**, then **no** $e \in S : e$ **is true** is equivalent to $\neg E_1 \wedge \neg E_2 \wedge ... \wedge \neg E_n$.

In SCL, high-order expressions are expressed by using `eval` clause. For example, the statement

```
eval all {
  verify r1:ospf { ... }
  verify r2:ospf { ... }
  verify link ...
}
```

returns true only if all verification rules return true.

You should notice that the statement above is by itself a verification rule. This means we can embed this rule to a higher-order expression as shown below:

```
eval some {
  verify ... // E1
  eval all {
    verify ... // E2
    verify ... // E3
  }
} // E1 OR (E2 AND E3)
```

4.4 Behavioral Verification

One common function on all types of network devices is data forwarding, from an incoming to an outgoing interface based on specific *Forwarding Control List* or FCL. For example, FCL on a router is its routing entries in the routing table. FCL on a firewall is its access control lists or ACLs. FCL on a NAT device is its address translation rules. Sometimes, the functions of routing, access control, and address translation can be physically integrated into one network device. In the following sections, we presents the formal representation of firewall, routing and NAT policies, then we discuss the behavioral verification at link and network levels.

4.4.1 Formal Representation of Forwarding Control List

An FCL, denoted as $\mathcal{A}$, contains a set of rules, where each rule has a constraint over some packet header fields and a decision. The decision of a rule depends on the type of FCL. A typical decision of filtering FCL is `accept` or `deny`. A typical decision of routing FCL is the outgoing interface or discard. For NAT FCL, a typical decision is to change some IP header fields.

When analyzing an FCL, we need to determine the set of IP packets that will have the same treatment. For example, when IP packets flow through a firewall device, the flow

will be divided into a number of groups based on the number of decisions taken by the firewall's FCL. If the firewall has only two actions (say accept and deny), then the flow will be divided into two groups: those packets that will be accepted and those packets that will be denied. RFC 3917 defines a flow as a set of IP packets passing an observation point in a network during a certain time interval. All packets belonging to a particular flow have a set of common properties such that a property a is defined as $a = f(x)$ where x can be:

1. one or more IP header field (e.g., source IP address), transport header field (e.g., source port number), or application header field.

2. one or more characteristics of the packet itself (e.g., number of MPLS labels).

3. one or more of fields derived from packet treatment (e.g., next hop IP address).

We denote a flow as π. We say a packet p belongs to a flow π (e.g., $p \in \pi$) if it completely matches all the defined properties of the flow. Without loss of generality we can assume, in this chapter, that the flow properties are taken from the following packet header fields: protocol, IP source address, IP destination address, source port address and destination port address. To represent a *set* of IP packets, IP source address and IP destination address are expressed in CIDR notation. Protocol and port addresses can be expressed as a single value or a range of values. In CSM model, a flow is defined by the following tuple: {`flow`, `proto`, `srcip`, `dstip`, `srcport`, `dstport`}. For example, the flow {flow, *any*, 10.1.2.0/24, 10.1.35.0/24, *any*, 1..1024} includes all possible packets originated from the subet 10.1.2.0/24 and destined to the subnet 10.1.35.0/24 with destination port ranges from 1 to 1024. The set of all possible packets {flow, *any*, 0.0.0.0/0, 0.0.0.0/0, *any*, *any*} is denoted as Π.

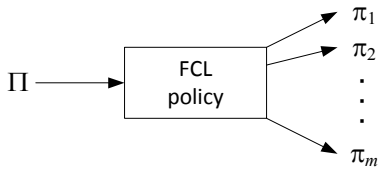


Figure 4.2: FCL policy with m different decisions partitioning flow Π into m sub–flows.

In this dissertation, we focus on three types of FCLs that decide routing, access control and address translation policies. The joint effect of the three FCLs will dominate flow manipulation and network behavior. Our methodology is to formalize, in the first step, the *effect* of the three FCLs on the flow Π as shown in Figure 4.2. As we mentioned before, the effect of an FCL with m different decisions is to partition the flow Π into a set of m *sub–flows* such that each sub–flow shares the same treatment. After that we develop a set of algorithms to verify the configuration from link–level to network–level.

Verifying the current configuration of FCLs is important since FCLs are difficult to configure correctly. There are several reasons. First, an FCL may consist of a large number (e.g., thousands) of rules. Second, these rules may be written by different administrations and at different times. Therefore, over the time, inconsistent FCL rules will be added that may create security holes by allowing malicious traffic or blocking legitimate traffic.

Due to the complexity of FCLs, they are commonly transformed to formal mathematical logical models such as Binary Decision Diagram (BDD) or Firewall Decision Diagram (FDD) [33], as we mentioned in Section 2.1. AutoConf adopts BDD due to its compactness, canonicity, and ease of manipulation. The formal model of an FCL policy depends on its type: filtering FCL, routing FCL or NAT FCL. However, we model an FCL rule, regardless of its FCL type, as follows. The information we need about the packet is the flow properties that we mentioned before. Therefore, we encode the information contained in a flow as a sequence of Boolean variables such that

$$F = F_{proto} \wedge F_{dstip} \wedge F_{srcip} \wedge F_{dstport} \wedge F_{srcport}$$

where F_{proto} is a Boolean function of 8 variables, F_{dstip} and F_{srcip} are Boolean functions of 32 variables, and $F_{dstport}$ and $F_{srcport}$ are Boolean functions of 16 variables. To illustrate the expression above, let us assume for simplicity that the IP address space is 2 bits and the remaining fields are 1 bit. This implies that a flow can be encoded using 7 Boolean variables. If a flow has the following information: srcip = 3, dstip = 2, proto = 0, srcport = any, and

Set Operation	BDD Operation	Description
Union	OR ($\vee$)	$F_1 \vee F_2$ represents the IP packets that satisfy F_1 or F_2
Intersection	AND ($\wedge$)	$F_1 \wedge F_2$ represents the IP packets that must satisfy F_1 and F_2
Not	Negation ($\neg$)	$\neg F = \Pi - F$
Is subset	Imply ($\rightarrow$)	$F_1 \rightarrow F_2$ means "is $F_1 \subseteq F_2$?" If the result $\equiv true$ (tautology) then F_1 is a subset of F_2

Table 4.2: Set operations and their equivalent BDD operations

dstport = 1. Then,

$$F_{proto}(x_0) = \neg x_0,$$

$$F_{dstip}(x_1, x_2) = x_1 \wedge \neg x_2,$$

$$F_{srcip}(x_3, x_4) = x_3 \wedge x_4,$$

$$F_{dstport}(x_5) = x_5, \text{and}$$

$$F_{srcport}(x_6) = 1.$$

where x_i is a Boolean variable that can take either 0 or 1. Notice that there are two assignments to bits/variables that satisfies F (i.e., F is true): first assignment is $F = F_{proto}(0) \wedge F_{dstip}(1,0) \wedge F_{srcip}(1,1) \wedge F_{dstport}(1) \wedge F_{srcport}(0)$ and the second assignment is $F = F_{proto}(0) \wedge F_{dstip}(1,0) \wedge F_{srcip}(1,1) \wedge F_{dstport}(1) \wedge F_{srcport}(1)$. Hence, F represents a "*set*" of two IP packets.

In summary, the semantic of a Boolean function (or expression) in our analysis is that it models a complex set. BDD provides compact representations for Boolean expressions, and it supports semantically set operations as shown in Table 4.2.

Now, let $r = \langle c_{proto}, c_{dstip}, c_{srcip}, c_{dstport}, c_{srcport}, a \rangle$ be an FCL rule where c_x is a constraint over the field x and a is an action to be taken. The Boolean expression of the rule r, denoted as F_r, is

$$F_r = F_a \wedge F_c \tag{4.2}$$

where

$$F_c = F_{proto} \wedge F_{dstip} \wedge F_{srcip} \wedge F_{dstport} \wedge F_{srcport} \tag{4.3}$$

and F_a is a Boolean function of 8 variables. This implies the total number of Boolean variables to model an FCL rule is 112 variables. The interpretation of the field `action` depends on the FCL type. For example, in routing policy, the field `action` encodes (forwarding to) the outgoing interface. Notice that the Boolean expression F_c encodes a set of IP packets that satisfy F_c and hence F_c represents a flow.

We introduce three functions to manipulate Boolean expressions, which are the *projection* function, its inverse function, and the *mask* function.

Projection function : is defined as $\Psi : F_\pi \times P \rightarrow F_a$, where F_π, P, and F_a are Boolean expressions for a flow, an FCL policy and an action, respectively. Ψ is used to determine the set of actions applied to an incoming flow π. For example, if P represents a routing FCL, then $\Psi(\pi, P)$ will return a Boolean expression that represents the set of outgoing interfaces that will be used to forward each packet in flow π.

Inverse of projection function : is defined as $\Psi^{-1} : F_a \times P \rightarrow F_\pi$, is used to determine the set of IP packets that will be treated according to the actions encoded in F_a. For example, if P is a filtering FCL and we need to determine the set of IP packets that will be denied, then we will use $\Psi^{-1}(F_{deny}, P)$ given that F_{deny} is the Boolean expression to encode "deny" action.

Mask function : is defined as $\tau : F \times h \rightarrow F'$ that takes as arguments two Boolean expressions F and h, and returns a new Boolean expression F' by resetting F at locations defined in h using existential quantifier operator. For example, if a flow is any packet sourced from 10.1.2.0/24 and destined to 10.1.23.0/24, applying τ function will result in a flow of any packet sourced from 10.1.2.0/24 given that $h = F_{dstip}$.

In all our discussion, we denote the Boolean expression of an FCL policy as P.

4.4.1.1 Firewall policy construction

Firewall policy has been extensively studied in [101, 33, 36]. Semantically, the Boolean expression of a filtering rule represents the set of IP packets that can pass through the associated interface. In [36], the firewall policy of *accepted* packets is constructed using the following formula:

$$P_a = \bigvee_{i \in I} (\neg F_r^1 \wedge \neg F_r^2 \wedge \cdots \wedge \neg F_r^{i-1} \wedge F_r^i) \tag{4.4}$$

where I is the set of indexes for rules that use `accept` as their actions. For example, if a filtering policy has 5 rules where r_1, r_3 and r_4 have `accept` as their actions, the Boolean expression that represents this policy is:

$$P_a = F_r^1 \vee (\neg F_r^1 \wedge \neg F_r^2 \wedge F_r^3) \vee (\neg F_r^1 \wedge \neg F_r^2 \wedge \neg F_r^3 \wedge F_r^4) \tag{4.5}$$

Here, we consider the filtering policy has two actions: `accept` and `deny`. In this case, the action field, a, can be ignored, and $P_{deny} = \neg P_{accept}$. In the case, we need to maintain all firewall actions, such as `accept`, `accept with logging`, `discard`, and `discard with logging`, we encode them with different numeric values.

The computation and memory cost of Equation 4.4 is quite high. For the example given above, to compute the policy expression when visiting rule 4, we need to maintain an extra BDD variable that represents the disjunction of rule 1, rule 2 and rule 3 (i.e., $F_1 \vee F_2 \vee F_3$). So, if the filtering FCL is too complex, the negation of this extra BDD variable may explode or slow down the policy computation dramatically (since it always maintain the disjunction of all previous rules).

An alternative way to construct a filtering policy is to traverse its rules in reverse order. In this way, we can *abbreviate* Equation 4.5 to the following expression:

$$P_a = F_r^1 \vee (\neg F_r^2 \wedge (F_r^3 \vee F_r^4)). \tag{4.6}$$

The logic is as follows. Initially we set $P_a = \phi$. Since the action at rule 4 is accept, we add the set of IP packets that satisfy rule 4 to P_a. At this stage, $P_a = F_r^4$. When visiting

rule 3, we also add the set of IP packets that satisfy rule 3 to P_a. At this stage, $P_a = F_r^3 \vee F_r^4$. When visiting rule 2, we need to remove those packets p such that $p \in P_a$ and $p \in F_r^2$ since rule 2 has higher priority than rule 3 and 4. At this stage, $P_a = \neg F_r^2 \wedge (F_r^3 \vee F_r^4)$. Finally, we visiting rule 1, we add the packets that satisfy rule 1 to P_a. As a result, we get Equation 4.6.

The above operations can be expressed as a recursive Boolean function T, such that:

$$T(i) = \begin{cases} a_i == accept \rightarrow T(i+1) \vee F_r^i, & T(i+1) \wedge \neg F_r^i \\ & \text{if } 1 \leq i < N \\ a_i == accept \rightarrow F_r^i, & false \qquad i = N \end{cases} \tag{4.7}$$

where $a \rightarrow b, c$ represents if–then–else operator (If a is true, then b, otherwise c). Therefore, the filtering policy P is computed as

$$P = T(1)$$

The construction algorithm needs only a single Boolean expression, say T, that will be updated while traversing the FCL rules in reverse order. We compared the performance of two algorithms that implement Equation 4.4 and Equation 4.7 with the same variable ordering. The experimental results discussed in Section 4.4 demonstrate that our formalization can achieve significant improvement on memory and computation efficiency over the previous work. In the case where Equation 4.4 has exploded, our formalization constructed the same firewall policy in just a few seconds.

The filtering policy $P = P_a$ determines the set of IP packets that are allowed to bypass. Therefore, if a flow π passes through a filtering FCL, the set of packets that are permitted can be expressed as:

$$F_\pi \wedge P \tag{4.8}$$

When configuring a filtering policy, the policy is usually applied to a network interface. A filtering FCL that is applied to an incoming traffic is called an inbound FCL. A filtering FCL that is applied to an outgoing traffic is called an outbound FCL. If a network device is configured with an inbound FCL and an outbound FCL, a traffic flow may pass both FCLs.

To compute the effect of inbound and outbound FCLs on network traffic, we model a physical interface as two unidirectional logical interfaces. Each physical interface has a unique number (within a device) as specified in CSM model. Therefore, a unidirectional logical interface is identified by its physical interface number along with a flag bit. The flag bit determines whether the logical interface is designated for incoming (0) or outgoing (1) traffic.

We aim at constructing a single Boolean expression that represents all filtering FCLs in a device so that complex verification queries can be efficiently handled. Let i be an interface number, d be a direction (0 for "in" and 1 for "out"), P_i^0 be the Boolean expression of the inbound FCL at network interface i, and P_i^1 be the Boolean expression of the outbound FCL at network interface i. P_i^d is computed using Equation 4.7. The overall filtering policy for a network device is expressed as:

$$P = \bigvee_{i \in \{1 \ldots I\}, d \in \{0,1\}} (F_i \wedge H_d \wedge P_i^d) \tag{4.9}$$

where I is the total number of network interfaces, F_i is the Boolean expression of the numeric value i and H_d is the Boolean expression of the flag bit d. Please note that if a unidirectional interface does not employ a filtering policy, its Boolean expression will become `true` to indicate the acceptance of all possible packets.

The Boolean variables to encode i and d are located within the `action` field. Since `action` field uses 8 bits, the the maximum value of I is 128. Therefore, we can express F_a as $F_a = F_i \wedge H_d$. As a result, if a flow π passes through interface i at direction d, the set of packets that are allowed is given by:

$$F_\pi \wedge P_i^d \;=\; F_\pi \wedge \Psi^{-1}(F_i \wedge H_d, P) \tag{4.10}$$

where P is given in Equation 4.9.

Another common verification query is to find the set of packets that may pass a device from any incoming interfaces to a specific outgoing interface. This query is particularly

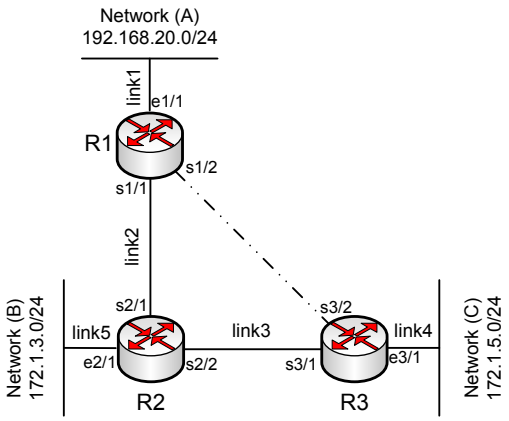


Figure 4.3: A network with three subnetworks connected via three routers

important if we want to ensure, for example, only certain packets that can reach a subnet from a specific gateway device, regardless of dynamic topology change. This situation has been addressed in [34] to demonstrate the lack of coordination between routing and security mechanisms. Consider an enterprise network in Figure 4.3. The network has three locations: A, B and C, connected via three routers R1, R2, and R3. Initially the routers are connected via two serial links (shown as solid lines). Assume that the enterprise security policy is for hosts only in location B (not C) to be able to communicate with servers in location A. Therefore, interface s1/1 is configured with an inbound packet filter that drops all packets sourced from 172.1.5.0/24. The security policy can be expressed using the following verification rule:

$$F_{\pi_0} \rightarrow P_1^0 \wedge P_3^1 \neq true$$

where π_0 is {flow, any, 172.1.5.0/24, 192.168.20.0/24, any, any}, interface s1/1 has number 1, and e1/1 has number 3. The verification rule returns true only when π_0 is *not* part of permitted IP packets (see Table 4.2).

Later, the enterprise has decided to improve network availability by adding a new link between R1 and R3 (shown as a dashed line). Unfortunately, the previous verification rule is no longer valid since IP traffic can come from interface s1/2. The updated (corrected)

verification rule is

$$F_{\pi_0} \rightarrow \left[(P_1^0 \wedge P_3^1) \vee (P_2^0 \wedge P_3^1)\right] \neq true$$

where inteface s1/2 has number 2.

In order to define a verification rule that is valid regardless of any topology change, we can express $E = (P_1^0 \wedge P_3^1) \vee (P_2^0 \wedge P_3^1)$ as

$$\begin{aligned} E &= (P_1^0 \wedge P_3^1) \vee (P_2^0 \wedge P_3^1) \\ &= P_3^1 \bigwedge (P_1^0 \vee P_2^0) \\ &= \Psi^{-1}(F_3 \wedge H_1, P) \bigwedge \Psi^{-1}(\neg F_3 \wedge H_0, P) \end{aligned}$$

Therefore, given the outgoing interface n and policy P, the verification rule is

$$F_{\pi_0} \rightarrow \Psi^{-1}(F_n \wedge H_1, P) \bigwedge \Psi^{-1}(\neg F_n \wedge H_0, P) \neq true \tag{4.11}$$

4.4.1.2 Routing policy construction

Unlike firewalls, routers do not select next hop based on the order of routing rules, but would rather find the longest prefix match. In addition, most routers support load-balancing when multiple paths exist. This implies multiple routing rules can be applicable to the same flow with their corresponding actions.

Each routing rule in routing policy is composed of a single matching field, which is the destination IP address. The action is forwarding packets to the next hop, which is determined by the outgoing interface along with the IP address of the next hop.

We construct the Boolean expression of a routing policy as follows. For each network prefix of length m, we first construct P_m and P_m^c such that

$$P_m = \bigvee_{k \in I_m} F_r^k \text{ and } P_m^c = \bigvee_{k \in I_m} F_c^k$$

where I_m represents the set of indexes for the entries that have destination prefix of length m, F_c^k represents the Boolean expression of the rule constraint without the action field (See Equation 4.3), and F_r^k is the Boolean expression of a routing entry as expressed in

Equation 4.2. The Boolean expression of the action field is expressed as $F_a = F_i \wedge H_1$, where i is the interface number. Then, we construct the routing policy, P, using the following recursive equation:

$$T(m) = \begin{cases} P_m \vee (\neg P_m^c \wedge T(m-1)) & 1 \leq m \leq 32, \\ P_0 & m = 0 \end{cases} \tag{4.12}$$

where $P = T_{32}$.

Applying the projection function Ψ on a routing policy P and a flow π (i.e., $\Psi(F_\pi, P)$) produces three possible outcomes:

1. The flow π is completely forwarded either to a single interface or multiple interfaces (i.e., $\forall p \in \pi$, the packet p will be forwarded to the next hop),

2. The flow π is completely discarded (i.e., $\Psi(F_\pi, P) == false$), and

3. The flow π is partially forwarded (i.e., $\exists p, q \in \pi$ and $p \neq q$, the packet p will be forwarded while the packet q will be discarded).

To ensure that the flow π has been completely forwarded by the routing FCL, we use the following verification rule

$$F_\pi \rightarrow \Psi^{-1}(\Psi(F_\pi, P), P) = true \tag{4.13}$$

Usually, we like to focus whether or not a flow π can reach a specific device. In other words, if the flow π passes through a router device, what flow that will be forwarded to the outgoing interface i? We answer this query using the following expression:

$$F_\pi \wedge \Psi^{-1}(F_i \wedge H_1, P) \tag{4.14}$$

4.4.1.3 NAT policy construction

Network Address Translation, NAT, is used by a device (e.g., firewall, router) deployed between a private and public networks. There are three forms of NAT FCLs: static NAT

FCL, dynamic NAT FCL, and overloading NAT (also known as PAT) FCL. In static NAT FCL, each rule translates a given source IP address to another pre-allocated source IP address. In dynamic NAT FCL, each rule translates a group of source IP addresses to another pre-allocated group of IP addresses. In overloading NAT FCL, each rule translates a group of source IP addresses to a single pre-allocated IP address but with different source ports.

Basically, a NAT rule is composed of a constraint over the source header field along with an action that determines the new source address. If an IP packet that is traversing from a private to public network matches the constraint, the source IP address of the packet will be replaced with the IP address specified in the action field. Otherwise, the packet will be *passed* without translation. The device that supports NAT service also keeps a reverse translation for the packets that are traversing from public to private network.

Modeling NAT FCL requires extra bits (up to 48 bits) to encode the action. This implies changing the number of bits dedicated for action field from 8 to 48 bits. To unify the encoding, we break a NAT rule ($c \rightarrow a$) into two rules: $c \rightarrow i$ and $a \rightarrow i$ where i is the rule index. This solution is valid because the number of rules in NAT FCL is usually very small. Using this scheme, the maximum possible number of rules for a NAT FCL is 256 rules.

Let $\mathcal{A}_c$ be the list that represents $c \rightarrow i$ and $\mathcal{A}_a$ be the list that represents $a \rightarrow i$. Let P_c and P_a be the Boolean expressions for $\mathcal{A}_c$ and $\mathcal{A}_a$, respectively. We calculate P_c and P_a as follows:

$$P_c = \bigvee_{i}^{N} F_i \wedge F_c$$

and

$$P_a = \bigvee_{i}^{N} F_i \wedge F_a,$$

where N is the number of rules in $\mathcal{A}$.

While constructing the Boolean expressions of P_c and P_a, we also construct $\acute{P}_c$ and $\acute{P}_a$ to represent the reverse translation when a flow is traversing from public back to private network. A constraint over the source IP address encoded in P_c becomes the constraint over

the destination IP address encoded in $\acute{P}_c$. We do the same encoding for $\acute{P}_a$. Therefore, for each NAT or PAT service, we maintain four policies: P_c, P_a, $\acute{P}_c$ and $\acute{P}_a$.

Now, let π be a flow that traverses from private to public network and passes through a static or dynamic NAT service, the effect of NAT service on the flow is expressed as

$$T(P_c \wedge F_\pi) \vee (\neg P_c \wedge F_\pi), \tag{4.15}$$

where $\neg P_c \wedge F_\pi$ is the set of packets that pass NAT service without translation, and $P_c \wedge F_\pi$ is the set of packets that have been translated under the transformation function T, and

$$T(x) = \tau(x, F_{srcip}) \wedge \Psi^{-1}(\Psi(x, P_c), P_a).$$

In case of PAT, we replace F_{srcip} with the expression $F_{srcip} \wedge F_{srcport}$.

The effect of NAT service on the flow π when traversing from public network to private network is expressed as

$$T^{-1}(\acute{P}_a \wedge F_\pi) \vee (\neg \acute{P}_a \wedge F_\pi), \tag{4.16}$$

where

$$T^{-1}(x) = \tau(x, F_{dstip}) \wedge \Psi^{-1}(\Psi(x, \acute{P}_a), \acute{P}_c).$$

In case of PAT, we replace F_{dstip} with the expression $F_{dstip} \wedge F_{dstport}$.

4.4.2 Link-level Behavior

Network behavior in terms of reachability and security is based on the behavior of each link in the network. We define a link behavior as the set of all possible packets passing through the link at any given time. Consider the enterprise network example in Figure 4.3. A host at location A sends an IP packet to a host at location C. The IP packet can reach subnetwork C if the network is configured properly to allow this packet passes through link 1, link 2, link 3 and link 4 as shown in Figure 4.3. The direction of the flow in link 1 is from network A to interface s2/1, the direction in link 2 is from interface s1/1 to interface s2/1, and so on. Therefore, the flow that passes through link 4 from R4 to network C at any given time

determines the set of IP packets reachable to hosts in network C. This flow relies mainly on another flow that passes link 3 from R2 to R3. Consequently, if we determine what IP packets permitted to flow from R2 to R3, then we can determine the IP packets permitted to flow from R3 to network C.

In CSM model, network links are modeled by using link primitive. Each link has a `class` and `ports`. The attribute `class` determines the link type (such as Ethernet, Serial or any user–defined class) while `ports` define the end points. In addition, each link is associated with one or two unidirectional *connection* primitives. Connection primitives are created by predefined rules based on the link class. For example, in case of "ethernet" and "serial" classes, we define two unidirectional connections. A connection tuple is defined as {connect, `id`, dev_1, $port_1$, dev_2, $port_2$, $\mathcal{F}$} where `id` is a universal identification number, $\mathcal{F}$, which will be explained later, is a Boolean expression, and the connection direction is from dev_1 to dev_2. For example, {link, ethernet, undefined, [{r1, 1}, {r2, 1}]} creates two predicates: {connect, 1, r1, 1, r2, 1, *true*} and {connect, 2, r2, 1, r1, 1, *true*}.

The Boolean expression $\mathcal{F}$ expresses the "*local*" effect of its connection on a flow. This effect results from applying FCL policies on this connection. Let us consider the connection from R1 to R2 as shown in Figure 4.3. The FCL policies that affect any flow passes through this connection are: routing FCL on R1, NAT FCL on R1, filtering (outbound) FCL applied on interface s1/1, and filtering (inbound) FCL applied on interface s2/1. Thus, for this connection and ignoring NAT policy, $\mathcal{F}$ is expressed as:

$$F_\Pi \wedge \Psi(F_1 \wedge H_1, P^{R1}_{routing}) \wedge \Psi(F_1 \wedge H_1, P^{R1}_{filtering}) \wedge \Psi(F_1 \wedge H_0, P^{R2}_{filtering})$$

If NAT policy should be applied, then $\mathcal{F}$ is given as:

$$V = F_\Pi \wedge \Psi(F_1 \wedge H_1, P^{R1}_{routing})$$

$$\left[T(V \wedge P^{R1}_{NAT}) \vee (\neg V \wedge P^{R1}_{NAT})\right] \wedge \Psi(F_1 \wedge H_1, P^{R1}_{filtering}) \wedge \Psi(F_1 \wedge H_0, P^{R2}_{filtering})$$

Algorithm 1 shows the steps to compute the Boolean expression $\mathcal{F}$ for each connection. We follow the order of operations based on many network devices such as Cisco devices.

Algorithm 1 Updating Connection Expression

Input: The connection `conn`
Output: The connection `conn`

{connect, ID, D1, P1, D2, P2, _} = conn
/* *Process outgoing interface* */
$F_\pi \leftarrow$ *true* /* *i.e. any possible flow* */
if D1 has Routing **then**
    $F_\pi \leftarrow$ Apply Eqn 4.14
end if
if D1 has NAT **and** P1 is external **then**
    $F_\pi \leftarrow$ Apply Eqn 4.15
end if
if D1 has Filtering at P1 **then**
    $F_\pi \leftarrow$ Apply Eqn 4.10
end if
/* *Process Incoming interface* */
if D2 has Filtering at P2 **then**
    $F_\pi \leftarrow$ Apply Eqn 4.10
end if
if D2 has NAT **and** P2 is internal **then**
    $F_\pi \leftarrow$ Apply Eqn 4.16
end if
return {connect, ID, D1, P1, D2, P2, F_π}

4.4.3 Network-level Behavior

The Boolean expression $\mathcal{F}$ captures the *local* effect of a connection on a flow. This expression tells us the set of all possible IP packets permitted to pass through at any given time. However, it does not tell us the "effective" IP packets that will flow through the connection. Some IP packets may be blocked or discarded before they reach the connection. In Figure 4.3, the effective IP packets that pass through the connection from R3 to network C are coming from link 3. The effective IP packets that pass through link 3 (from R2 to R3) are resulted from link 2 *plus* link 5. Thus, if we determine the effective IP packets that pass through a connection, we can evaluate the network behavior.

We model a network topology as a directed graph $G = \langle V, E \rangle$, where V is the set of vertices and E is the set of edges. Each vertex $v \in V$ represents a unidirectional connection and it is labelled by its connection *id*. A directed edge $[u, v]$ in G is constructed when the following two conditions hold:

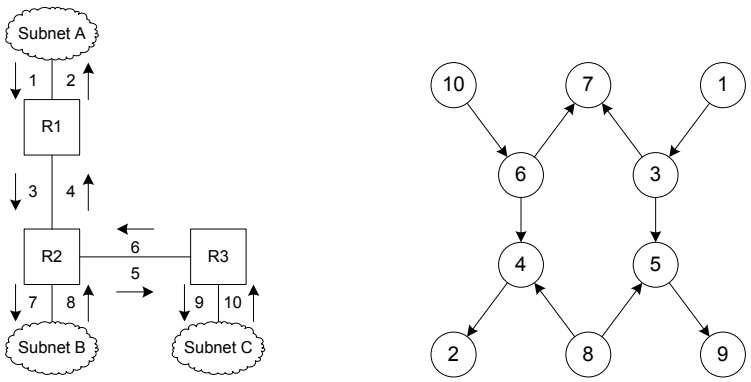


Figure 4.4: The graph model of a simple network

- both vertices u and v are sharing a common device d such that the device d has an incoming interface from connection u and an outgoing interface to connection v.

- the incoming and outgoing interfaces of device d are not the same.

This model divides vertices into three disjoint sets, source vertices S, sink vertices T and middle vertices M. Source vertices and sink vertices represent end-to-end connections in a network topology. This means for each end point there is at least one connection $v \in S$, one connection $u \in T$, and $v \neq u$. Consider the example network in Figure 4.4. The figure on the left side shows the enterprise network as in Figure 4.3 and the figure on the right side shows its representation in our graph model. Each link has two unidirectional connections. The numbers beside links represent connection IDs. The arrows represent the direciton of each connection. If an IP packet is traversing from Subnet A to Subnet C, the packet will pass through the following connections: 1, 3, 5, and 9. Vertices $2, 7$ and 9 are sink vertices. Vertices $1, 8$ and 10 are source vertices.

Now, let $\mathcal{E}_v$ be the effective flow that passes through connection v. We can obtain $\mathcal{E}_v$ by computing the disjunction of all paths from the source vertices to the vertex v, in which each path is computed by the conjunction of all connection's Boolean expressions that construct

the path. For example,

$$\begin{aligned}\mathcal{E}_5 &= (\mathcal{F}_5 \wedge \mathcal{F}_8) \vee (\mathcal{F}_5 \wedge \mathcal{F}_3 \wedge \mathcal{F}_1) \\ &= \mathcal{F}_5 \wedge [\mathcal{F}_8 \vee (\mathcal{F}_3 \wedge \mathcal{F}_1)] \\ &= \mathcal{F}_5 \wedge (\mathcal{E}_8 \vee \mathcal{E}_3)\end{aligned}$$

where $\mathcal{E}_8 = \mathcal{F}_8$ and $\mathcal{E}_3 = \mathcal{F}_3 \wedge \mathcal{E}_1$.

Algorithm 2 describes a depth first search algorithm to compute $\mathcal{E}_t$ where $t \in T$. The network–level behavior can then be computed by applying Algorithm 2 for each sink vertex. This algorithm ensures that $\mathcal{E}_v$ is computed only once unless v is included in a loop. In this case, for each sink vertex we reset those vertices that are included in some loop by marking them as unvisited and setting its $\mathcal{E}$'s value to $false$. The reason of resetting is to ensure correct computation when AutoConf receives initial configuration with no information about routing policies. Ignoring the cost of BDD operations, the running time over all sink vertices using Algorithm 2 is $O(|L| \times |T|)$ where L represents the set of vertices that are included in some cycle in the graph G.

4.4.4 Impact of Configuration Change

Here we show how AutoConf handles configuration change efficiently. We distinguish between two impacts of dynamic configuration: Network topology change and Connection change. Network topology change occurs when adding or removing physical links or any modification that triggers routers to update their routing tables. When it occurs, we need to rebuild routing policies, and recompute $\mathcal{F}$ and $\mathcal{E}$ values. Connection change is any modification that occurs at specific connection like modifying ACL rules for a specific service or updating Subnet addresses. For example, in Figure 4.4, if we add a new inbound filtering policy in connection 4 at router R1, then we need to rebuild the BDD of filtering policy of router R1 using Equation 4.10, next we recompute $\mathcal{F}_4$ using Algorithm 1, and finally we need to update $\mathcal{E}_4$ by using Algorithm 3. The running time of Algorithm 3 is $O(|V|)$.

Algorithm 2 Algorithm to construct $\mathcal{E}$ of vertex $t \in T$

Input: The graph $G = \langle V, E \rangle$ and vertex $t \in T$
Output: The set of $\mathcal{E}$

set $t' \leftarrow$ the opposite connection of t
store the status of t' and $\mathcal{E}_{t'}$
mark t' as visited and set $\mathcal{E}_{t'} \leftarrow$ **false**
reset all vertices in V that are involved in a cycle
`compute(t)`
restore t' to its original values

Procedure: `compute(`v`)`

if v is **not** visited **then**
    mark v as visited
    if $v \in S$ **then**
        $\mathcal{E}_v \leftarrow \mathcal{F}_v$
    else
        $X \leftarrow$ **false**
        for all $u \in V$ such that $[u, v] \in E$ **do**
            `compute(`u`)`
            $X \leftarrow X \vee \mathcal{E}_u$
        end for
        $\mathcal{E}_v \leftarrow \mathcal{F}_v \wedge X$
    end if
end if

Algorithm 3 Algorithm to update $\mathcal{E}$ of vertex $v \in V$

Input: The graph $G = \langle V, E \rangle$ and vertex $v \in V$
Output: The updated set of $\mathcal{E}$

reset all vertices in V that are involved in a cycle
`update(`v`, `v`)`

Procedure: `update(`v`, `t`)`

mark v as unvisited
compute(v)
for all $u \in V$ such that $[v, u] \in E$ **do**
    if $u == t$ **then**
        continue
    else
        `update(`u`, `t`)`
    end if
end for

4.4.5 SCL Language Related to Behavioral Verification

SCL supports two types of queries: *show* query and *assert* query. Show query displays either the set of packets that represents a flow or the set of actions performed on a given flow.

Assert query provides true/false answers.

4.4.5.1 SHOW Query

The general syntax of show query is:

```
policy <device>|list|* : <action>|* {
    [show <flow>|<action>
    when (<constraint>) [;]]+
}
```

The constraint field consists a set of `field = value` conditions where `field` can be `proto`, `srcip`, `dstip`, `srcpx` (src subnet mask), `dstpx` (dst subnet mask), `srcport`, `dstport`, `action`, `oface` (for outgoing interface), `iface` (for incoming interface). The value can be an atom, integer, IPv4 address, IPv4 address/prefix, or a list (enclosed by []). For example, we need to display what actions (outgoing interface) will be taken when a given flow passes through a routing policy in router `r2`. The query is:

```
policy r2 : routing { // service-level
    show action when (dstip = 10.2.3.0/24);}
```

The next query displays the set of packets that passes router r1 through outgoing interface 2:

```
policy r1 : * { // device-level
    show flow when (oface = 2) }
```

4.4.5.2 ASSERT Query

The SCL format for assert statement is

```
policy <device>|list|* : <action>|* {
    [ assert ( <constraint> ) ]+
}
```

The following query returns 1 (true) if there is a path from subnet s1 to a Web server in subnet s2:

```
policy [s1, s2]:path {
  assert (action=1, dstip=72.10.2.101, dstport=80) }
```

Two or more assert statements can be connected logically by using `eval` statement. The `eval` statement is based on the following formula: $Q : F$ where Q is quantifier that can take the following values: **all**, **some**, or **none** and F is a set of logical functions. For example, the following query ensures that there is a connection between subet s1 and the Web server at subnet s2:

```
eval all {
   policy [s1, s2]:path {
      assert (action=1, dstip=72.10.2.101, dstport=80);}
   policy [s2, s1]:path {
      assert (action=1, srcip=72.10.2.101, srcport=80);}
}
```

4.5 Summary

With the increasing complexity of network configuration, verifying network behavior is an essential activity to ensure the correct operation of a network. This chapter presents a configuration verification solution that partition the problem space into two categories: consistency verification and behavioral verification. We present a formalization methodology to verify the consistency of configuration parameters that span multiple network devices. In behavioral verification, we present a graph-based model along with Binary decision diagram (BDD) to formally capture the network behavior in terms of reachability and security. In addition, we extend Structure Configuration Language (SCL) to provide an expressive query interface for network administrators.

Chapter 5

Configuration Automation

5.1 Overview

Managing IP networks is considered a challenging task due to several factors: heterogeneous network, deployment of various network services and guaranteeing its quality of service, different provisioning requirements, and primitive support from network devices. To mitigate management complexity, there is a growing consensus about the need for an automated network management system especially for environment where it requires quick services deployment, almost near to real-time to avoid service disruption such as tactical military environment [18, 92].

Policy–driven management is the most widely adopted approach for network management. As reported by Chen at. el. [19], Tier-1 Internet service provider (ISP) and enterprise networks are managed by following a standard practice called method of procedure (MOP). This practice is basically a policy–based approach under which there are a set of rules governing the choices of desired network behavior. Each rule consists of a set of actions to be performed and a set of conditions to be checked before such actions can be taken.

The main features of policy–based management are its flexibility and scalability for managing complex, large–scale networks [23]. Scalability is achieved by applying the same

policy rule to large sets of devices and services, while flexibility is achieved by separating the policy from the implementation of the managed system. Policy–based management is widely adopted by IETF and DMTF standard organizations.

This chapter focuses on managing and automating IP network configuration using policy–based management. In this context, required or desired behavior of network operations and its services are expressed in terms of policies. These policies are enforced by AutoConf by sending NETCONF configuration commands as illustrated in Figure 5.1. Automating network configuration using policy–based approach has several challenges. The following paragraphs describe them.

As we mentioned, policy rules are specified in a high-level language in order to reduce the configuration complexity. For example, a policy may state that if there is a network interface in Subnet 1 that does not belong to the network address 10.1.1.0/24, then invoke the action ifconfig() with appropriate parameter values. This rule is applied to multiple devices where each device supports multiple interfaces. In order to enforce this rule, the system must check the IP address of each network interface in Subnet 1. If it finds one interface that does not comply to the policy, it will trigger ifconfig() action on that interface. Now, if the manager has defined many policies and the network has experienced multiple changes (the system will be notified by a monitoring system), the management system should iterate over the policy rules *for each change* to determine the set of actions along with the parameter lists. The problem will be exacerbated if these policies are complex, having multiple conditions connected by Boolean operators (such as AND, OR, etc.). Moreover, the management cannot only rely on the current changes to determine the set of actions but also on the previous changes. Because when the management system aggregates the previous and the new changes, the satisfiability of some policies might be completed. In other words, all conditions for those policies are met. Therefore, our first challenge is to develop a model that captures the complexity of the policy rules as well as the current network state efficiently. The model should allows us to easily discover any inconsistency or conflict within a policy.

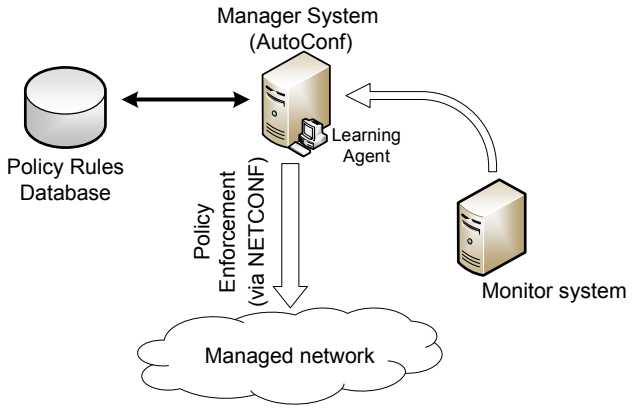


Figure 5.1: Policy–based management

The second challenge is that the model should scale well in large–scale networks. If a network consists of hundreds of devices, the network state will be huge specially when the network is running several services.

The last challenge is that the management system may face multiple actions that should decide on an action or strategy to handle any conflict during network operation. In order to decide the most effective strategy, the management system should have a detailed information of each element in the network. This will improve the correlation accuracy when the system is trying to correlate the current network state and the current policies with the expected future network state. This correlation enables the management system to learn from its past experience and optimize the selection of future actions.

Considerable research work has been done on policy–based management (see Section 2.5). Most work mainly focused on building policy–based framework, policy specification and policy language. In environment where multiple policy rules may be triggered, policy selection is often based on statically configured work–flow [19] performed by an administrator. As the network becomes more complex; however, policies will be deficient to handle and tackle unseen work–flow. In this case, human involvement is required and manual configuration is performed which may generate misconfiguration. Therefore, it is imperative for configuration management system to automate policy selection in order to deal with not only configuration process but also misconfiguration that may occur. Several researches [7, 91]

have proposed approaches to implementing policy adaptation. These approaches consider system automation in a single device. Due to the complexity of policy rules and the difficulty to represent network state, there are a few attempts in policy adaptation [6, 95]. This chapter presents an attempt to implement Reinforcement Learning (RL) for large-scale network.

We use Binary Decision Diagram (BDD) to tackle the complexity of network description and resolve the aforementioned challenges. BDD has been used to formally represent service–oriented policies such as Firewall and IPSec where the number of parameters (such as IP header parameters) is limited and very few. We show how we can represent a formal model for a large set of parameters that belong to different services spanning over multiple network devices. We propose a set of formal models to capture the policy rules and network operational status. We use RL technique called Q-learning that allows AutoConf to learn in real–time in order to figure out the best strategy to handle any conflict or any QoS degradation according to an existing set of requirements.

5.2 Policy Structure

There are several policy languages that specify policy rules and actions. We focus here on the logical representation. We assume a policy is consisting of a set of rules such that each policy rule has a *conjunctive* set of conditions along with a list of actions that change the network behavior. A policy rule may have other attributes such as policy name, policy type and whether the rules is enabled or not [24]. Formally, we define a policy rule as a tuple $p = \langle C, A \rangle$ where C is a list of conditions, and A is a list of actions.

5.2.1 Policy Condition

Policy conditions are based on metrics that describe the network behavior such as flow characteristics (e.g., Type of Service or ToS IP header field), traffic parameters (e.g., round–trip

delay, jitter or throughput), performance parameters (e.g., link utilization, link bandwidth, packet loss probability), and configuration parameters (e.g., network interfaces' status, enabled network protocols such as OSPF or ISIS). Moreover, many enterprises and ISP networks rely on service level agreement (SLA) to guarantee QoS to end users or applications. These SLAs are eventually a set of QoS metrics. For example, an enterprise network establishes an SLA that states "*A video application between clients in site A and a media streaming server in site B should receive Gold service*" [60]. The network administrator defines "Gold service" as a network service with lowest delay and lowest packet loss, and Differentiated Service architecture is deployed in the network.

We define a policy condition $c \in C$ as $c = \langle$ `metric-spec`, $\mathcal{V}$ $\rangle$, where $\mathcal{V}$ is an interval of values. We define metric–spec as a tuple $m = \langle$ `target-name`, `service-name`, `metric-name` $\rangle$. For examples:

1. the status of interface `e1/1` in router `R1` can be expressed as $\langle$`R1`, `interface`, `e1/1`$\rangle$,
2. all interfaces in router `R1` can be expressed as $\langle$`R1`, `interface`, `any`$\rangle$,
3. the number of clients accessing the media streaming server `server01` can be expressed as $\langle$`server01`, `mediaStreaming`, `num-clients`$\rangle$, and
4. link x bandwidth can be expressed as $\langle x$, `link`, `bandwidth`$\rangle$.

A policy condition c is a relational expression that has a relational operator such as "$=$", "$\neq$", "$<$", "$\leq$", "$>$", or "$\geq$". As such, the relational expression identifies the set of values (i.e., $\mathcal{V}$) under which an action $a \in A$ will be executed. The set $\mathcal{V}$ can be a single value (e.g., `if <R1,interface,e1/1> == false then action--list()`), or it can be a range of values (e.g., `if <Server01, mediaStreaming, num-clients> > 100 then action--list()`). In our analysis, the set $\mathcal{V}$ is always expressed as an interval. Table 5.1 summarizes the relationships between the set $\mathcal{V}$ and the relational operators.

We assume that all metrics used to describe the network behavior are 64-bit non-negative integer values. In case of Boolean metrics, we use the values 1 and 0 to indicate true and

Relational Operator	Example	The set $\mathcal{V}$
$=$	$m = a$	[a, a]
$\neq$	$m \neq a$	$(-\infty, a) \cup (a, +\infty)$
$\leq$	$m \leq a$	$(-\infty, a]$
$\geq$	$m \geq a$	$[a, +\infty)$
range	$m \geq a$ AND $m \leq b$	$[a, b]$

Table 5.1: Expressing a relational operator as a set of values where m is a metric–spec, and a and b are numbers.

false, respectively. In case of percentage metrics, we use the values from 0 to 100. In case of floating-point values, we round it to the nearest integer. $-\infty$ and $+\infty$ are expressed as 0 and $2^{64} - 1$, respectively.

5.2.2 Policy Action

A policy action defines the configuration change that needs to be performed when its rule condition holds true. An action is defined as a function with a name and a possible set of parameters. In many implementations, a policy rule may have several actions to indicate different approaches to handle, for example, undesirable behaviors. The manager needs to select one of these actions based on the current state of the network behavior. Later in this chapter, we will mention a learning methodology in how to select an optimal action.

In our approach, each action is defined as $a = \langle$`action-id`, `action-name`, `parameters`, `action-body`$\rangle$. Action body consists of optional assertion clauses, a SET request, and an optional GET request to verify the new change. The assertion clause defines the set of extra prerequisite before sending SET request. For example, to configure MPLS in a network, the network must enable OSPF protocol first. Similarly, before configuring OSPF, the interfaces must initially be configured. If one assertion clause fails, the action is considered failed.

Using SCL commands, SET request is equivalent to "manage" command and GET request is equivalent to "verify" command. In case where the action function has a "verify" command, it must provide a feedback to AutoConf system about the new change. In case where the action function has no "verify" command, AutoConf will receive the feedback from the monitor system.

It is desirable that the action function consists of a single "manage" command because this will allow AutoConf to evaluate the effectiveness of each individual command. For example, if the action consists of two "manage" commands, then it will be difficult to understand the impact of these commands; if the "verify" command returns false, is it because of the first command, the second command or both? By having a single "manage" command, AutoConf can have more accurate analysis of the actions performed during its life cycle and can decide the proper order to execute.

5.2.3 Policy Type

There are several types of policies. In this dissertation, we consider only two types of policies: Configuration policy and Expectation policy [79].

The configuration policies describe how to configure a service where the conditions tell when and which devices are needed to be configured. List 1 shows an example of a configuration policy to set static configuration parameters based on the Service Level Agreement (SLA) requirements.

```
At every edge router:
     if (Time >= 8am) and (Time <= 11am) and (IPdest = 123.4.5.6) then
         setParamters(Transmission = 200Kbps,
                      PacketLoss = 10,
                      Delay = 100)
```

List 1: Configuration Policy Example

Expectation policies describe configuration setup to correct a conflict or a violation and to ensure the service is running as expected. An example for an expectation policy is shown

in List 2.

```
For every device X in Subnet 1:
     if (ip-address not IN 123.4.5.0/24) then
         ifconfig(X)
```

List 2: Expectation Policy Example

5.3 Automation Model

In policy–based management, the network operation is orchestrated by an active set of policies. In other words, policy rules are either enabled or disabled, and the desired network behavior is achieved by enabling and disabling those policy rules. Our approach is to define a set of requirements, which expresses administrator's intentions and requested network performance. These requirements are derived directly from the policy rules. Therefore, we model network dynamics as a tuple $K = \langle \mathcal{P}, \mathcal{S}, \mathcal{Q}, \mathcal{M}, \mathcal{A} \rangle$ where

- $\mathcal{P}$ is a set of all policy rules such that $\mathcal{P} = P_1, P_2, \cdots, P_N$ where N is the number of policy rules,
- $\mathcal{S}$ is a set of states such that each state is defined as a tuple $S = \langle$ `target-name`, `service-name`, `metric-name`, `value` $\rangle$,
- $\mathcal{Q}$ is a set of requirements that define the desired network behavior.
- $\mathcal{M}$ is a set of metrics used to describe the status of a network operation.
- $\mathcal{A}$ is a set of actions or procedures to be carried out at certain circumstances.

A network may consist of hundred or thousands of network devices and each device may have hundreds of metrics (or configuration parameters). Therefore, the network status contains a huge set of metrics that needs to be manipulated. To handle this complexity, we use BDD to represent network requirements as well as network states. In Chapter 7, we

show the efficiency of our model by running a set of simulation experiments with different network topologies.

To optimize the selection of action based on the current network state and requirement set, we implement RL with Dyna-Q algorithm. In this section, we first show how to model network requirements using BDD. Then we show how to automate action selection by using RL technique.

5.3.1 Policy Representation

The management system requires a set of *requirements* to be achieved and maintained during the life cycle of a network. These requirements are actually derived from the policy rules. If a policy rule represents a violation, then the negation of the policy conditions constructs a requirement as shown in Figure 5.2. Let us consider again the following policy: "if there is a network interface in Subnet 1 that does not belong to the network address 10.1.1.0/24 then invoke the action ifconfig()". The system checks the Subnet 1's repository. If the repository indicates that there are two routers (say R1 and R2) and each with two interfaces (say e0/0 and s0/0), then the system will create four requirements.

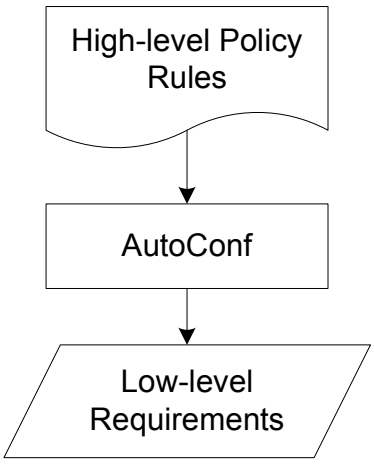


Figure 5.2: High-level policy rules are translated to low-level requirements

Before we list these requirements, we need to define a requirement formally. A require-

ment is a tuple $q = \langle I,$ target–name, service–name, metric–name, $\mathcal{V}, A\rangle$ where I is a requirement ID. List 3 shows a list of requirements derived from the aforementioned policy. A requirement set $\mathcal{Q}$ is the set $\{q_1, q_2, \cdots, q_n\}$ where n is number of requirements in $\mathcal{Q}$.

```
<10, R1, e0/0, ip-address, 10.1.1.0/24, [ifconfig($T, $S)]>,
<11, R1, s0/0, ip-address, 10.1.1.0/24, [ifconfig($T, $S)]>,
<12, R2, e0/0, ip-address, 10.1.1.0/24, [ifconfig($T, $S)]>,
<13, R2, s0/0, ip-address, 10.1.1.0/24, [ifconfig($T, $S)]>,
```

List 3: Generated Requirements from a given policy

Network administrator can manually modify the requirement set since requirement IDs play a crucial role to determine the semantic of the requirement set. List 4 shows a requirement set of a single requirement but with two different goals. This indicates that satisfiability of requirement ID (1) is achieved by satisfying, at least one, of its goals. This situation is more convenient for high-availability environment. List 5 shows a set of two requirements where each requirement has one goal. The network tries to satisfy these requirements during its life-cycle.

We use Binary Decision Diagram to represent the requirement set. As we mentioned a requirement q has six fields: requirement ID, target name, service name, metric name, value interval and action list. Therefore, the Boolean function of q is the conjunctive set of Boolean variables that maps the binary representation of each field. This means that the requirement q is encoded as:

$$F_q = F_I \wedge F_{TI} \wedge F_{SI} \wedge F_{MI} \wedge F_v \wedge F_A, \tag{5.1}$$

where I is the requirement ID, TI is the target ID, SI is service ID, and MI is metric ID. TI, SI and MI are constructed using hashing functions of target, service and metric names.

The Boolean function F_I is constructed directly from the binary representation of the requirement ID. For example, if the requirement ID is 9 and F_I uses x_0 to x_3 as Boolean variables, then $F_I = x_3 \wedge \neg x_2 \wedge \neg x_1 \wedge x_0$. Notice that the only assignment that makes F_I true is 1, 0, 0, and 1 for x_3, x_2, x_1, and x_0, respectively.

```
<1, R1, interface, s0/0, 1, [enable_interface($T, $M)]>
<1, R1, interface, s0/1, 1, [enable_interface($T, $M)]>
```

List 4: Single requirement with two different goals

```
<10, R1, interface, s0/0, 1, [enable_interface($T, $M)]>
<20, R1, interface, s0/1, 1, [enable_interface($T, $M)]>
```

List 5: Two different requirements

Target ID can be a single ID to indicate that the requirement q is applied to a single target or a domain ID to indicate that the requirement q is applied to a group of devices. In case of a domain ID, the satisfiability of this requirement is achieved if there is at least one target satisfies the requirement. Also, Target ID can be "any" to indicate that the requirement q is applied to any target defined in a network. Therefore, the Boolean function of F_{DI} is

$$F_{TI} = \begin{cases} F(hash(\text{target name})) & \text{for a single target} \\ \bigvee_{k \in D} F(k) & \text{for a domain target} \\ true & \text{for any target} \end{cases}$$

The variable D is the set of targets (or devices) in a domain based on CSM parent–child relationships. For example, the metric ⟨R1, s0/0, PacketLoss⟩ is formulated as $F_{H(\text{“R1”})} \wedge F_{H(\text{“s0/0”})} \wedge F_{H(\text{“PacketLoss”})}$ where $H()$ is a hash function.

The Boolean function F_v is constructed by the disjunction of powers of two values spanning the interval $\mathcal{V}$. For example, $[3, 7] = [3, 3] \cup [4, 7]$ and can be encoded (using 3 bits) as $F_v = (\neg x_{12} \wedge x_{11} \wedge x_{10}) \bigvee x_{12}$ assuming that x_{10} to x_{12} are used to encode F_v.

The Boolean function F_A is given as

$$F_A = \bigvee_{k=1}^{m} F_{a_k}$$

where $A = \{a_k, k = 1, 2, \cdots, m\}$, a_k is an action ID, and F_{a_k} is constructed directly from the binary representation of the action ID of a_k.

Now, let $\mathcal{Q} = \{q_1, q_2, \cdots, q_M\}$ be a set of M requirements. We represent Q as a Boolean

function $F_{\mathcal{Q}}$ such that

$$F_{\mathcal{Q}} = \bigvee_{k=1}^{M} F_{q_k}. \tag{5.2}$$

5.3.2 Policy Manipulations

Representing requirement set $\mathcal{Q}$ using BDD allows us to manipulate it using simple BDD operations. First, we start with disabling a requirement. A requirement q can be disabled and removed from $\mathcal{Q}$ by using the following equation:

$$F_{\mathcal{Q}} \wedge \neg F_q \tag{5.3}$$

Sometime we have partial information about the requirement like, we only know the target, the service and the metric name. Then we can disable all requirement pertaining to this metric–spec by using the following equations:

$$S = F_{H(\text{target})} \wedge F_{H(\text{service})} \wedge F_{H(\text{metric})}$$

$$F_{\mathcal{Q}} \wedge \neg S$$

Enabling a requirement q can be expressed as:

$$F_{\mathcal{Q}} \vee F_q \tag{5.4}$$

Finally, we can check if a given requirement specification conflicts with another requirement in $\mathcal{Q}$. This can be achieved by checking the result of the following logical expressions:

$$S = F_{TI} \wedge F_{SI} \wedge F_{MI} \wedge F_v,$$

$$F_{\mathcal{Q}} \wedge S == true$$

If the logical expression $F_{\mathcal{Q}} \wedge S$ returns $true$, it implies there is a conflict. Otherwise there is no conflict.

5.3.3 System State Representation

As we mentioned, network behavior is described by using a set of metrics. The current values of these metrics define the current network operation. We assume that the monitor system provides to the AutoConf system the following information when it reports the status of a metric:

metric state m ::= <`target name, service name, metric name, observed value`>.

First, let M_t be a collection of metric states collected at time t. At time t_0, the network state $\mathcal{S}$ is clearly equivalent to M_{t_0}. For time $t > t_0$, the network state is updated based on the current set M_t and the previous network state $\mathcal{S}_{old}$. Let t_1 and t_2 be two consecutive times such that $t_2 > t_1$. Let S_{t_1} be the network state at time t_1 and let M_{t_2} be the set of states that have been received from the monitor system. Then the network state at time t_2 can be expressed as:

$$S_{t_2} = M_{t_2} \cup \left[S_{t_1} - \left(S_{t_1} \cap M'_{t_2}\right)\right]. \tag{5.5}$$

where M' is constructed by setting each metric state $m \in M$ to "any".

Next, we show how to represent a network state using BDD. First, we encode each metric state m as:

$$F_m = F_{TI} \wedge F_{SI} \wedge F_{MI} \wedge F_v.$$

Second, we compute F_M as:

$$F_M = \bigvee_{k=1}^{K} F_{m_k}, \tag{5.6}$$

where $m_k \in M$. Last, the network state can be expressed using Equation 5.5 as:

$$F_{\mathcal{S}} = F_M \vee \left[F_{\mathcal{S}_{old}} \wedge \neg \left(F_{\mathcal{S}_{old}} \wedge F_{M'}\right)\right]. \tag{5.7}$$

where $F_{M'} = \tau(F_M, F_v)$ and $\tau()$ is the mask function as given in Chapter 4.

AutoConf system compares the current network state with the requirement set $\mathcal{Q}$ to determine whether it needs to take an action or not. Based on the current network state, the requirement set $\mathcal{Q}$ is divided into the following subsets:

1. subset $\mathcal{Q}_s$ such that each requirement $q \in \mathcal{Q}_s$ is "*satisfied*". We say a requirement q is satisfied when at least one of its goals is met based on the current values of network metrics,

2. subset $\mathcal{Q}_u$ such that each requirement $q \in \mathcal{Q}_u$ is "*unknown*". We say a requirement q is unknown when we cannot determine the satisfiability of all of its goals based on the current values of metrics, and

3. subset $\mathcal{Q}_v$ such that each requirement $q \in \mathcal{Q}_v$ is "unsatisfied". We say a requirement q is unsatisfied when all of its goals are unsatisfied.

Notice that $\mathcal{Q} = \mathcal{Q}_s \cup \mathcal{Q}_v \cup \mathcal{Q}_u$ and $\mathcal{Q}_s \cap \mathcal{Q}_v \cap \mathcal{Q}_u = \Phi$. Therefore, it becomes clearly that the objective of AutoConf system is to maximize the fulfillment of the requirement set $\mathcal{Q}$, by minimizing the two conflict sets $\mathcal{Q}_v$ and $\mathcal{Q}_u$ as much as possible.

Using our formal model, we compute $\mathcal{Q}_s$ using the following expression:

$$F_{\mathcal{Q}} \wedge F_{\mathcal{S}}, \tag{5.8}$$

we compute $\mathcal{Q}_v$ using the following expression:

$$\neg F_{\mathcal{Q}} \wedge \tau(F_{\mathcal{Q}}, F_v) \wedge F_{\mathcal{S}}, \tag{5.9}$$

and we compute $\mathcal{Q}_u$ as:

$$F_{\mathcal{Q}} \wedge \neg \left(F_{\mathcal{Q}_s} \vee F_{\mathcal{Q}_v}\right). \tag{5.10}$$

Using the above analysis, we are ready to define the *system state* that the learning agent in AutoConf system will use to interact with the environment. Given a requirement set $\mathcal{Q}$ and a network state $\mathcal{S}$, the system state $\hat{\mathcal{S}}$ is defined by the tuple $\langle \mathcal{Q}_v, \mathcal{Q}_u \rangle$. Please note that there are two different types of states: network state and system state. Network state is the current operational status, while system state is derived from the requirement set and the network state.

When a managed network is operating as required, the learning agent should be in state $\hat{\mathcal{S}} = \langle \phi, \phi \rangle$, which means that all requirements have been checked and satisfied. We call

this state *the goal state*. When one or more requirements are unsatisfied, the set $\mathcal{Q}_v \neq \phi$ or $F_{\mathcal{Q}_v} \neq false$. The learning agent then *decodes* $F_{\mathcal{Q}_v}$ to extract the action list along with the metric specifications: target name, service name and metric name. Therefore, the objective of the learning agent is to move *efficiently* the system state from undesired state to the goal state by constructing a plan adaptively. The plan describes the optimal set of actions to reach the goal state. The following section shows how to build up this plan.

5.3.4 Action Selection

We model our system using a finite state machine. In this context, the management system encounters a set of actions extracted from $\mathcal{Q}_v$ and $\mathcal{Q}_u$ and must decide the next action to be performed at each state. This section shows how the management system learns effective decision-making policies when it interacts with the managed network.

As we mentioned in Chapter 2, an agent in RL learns optimal policy by interacting with its environment. In every time step t, the learning agent performs the following tasks:

- observing the environment current state s_t at time t,
- determining the next action (using for example ϵ-greedy algorithm) from a list of legal actions at state s,
- executing the action and observing the new state s_{t+1}, and
- receiving a reward r_t.

The main objective of RL algorithm is to maximize the cumulative reward it receives. This can be achieved by estimating action-value function $Q(s, a)$ which assigns a value when taking action a at state s. In Q-learning, $Q(s, a)$ is estimated using the following equation:

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha \left[r_t + \gamma \max_{a_{t+1}} Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t) \right] \tag{5.11}$$

Here α is a learning rate factor, γ is a discount factor between 0 and 1 expressing how strongly present value relies on future rewards, and r_t is the immediate reward. The $Q(s, a)$

measures how good it is for the management system to execute action a in a given state s. Several powerful theorems guarantee that Q-learning converges with probability of 1. Dyna-Q algorithm 4 proposed by Sutton supports system model and management policy and it is closely related to the adaptive method we develop. The algorithm estimates $Q(s, a)$ using Equation 5.11. The algorithm starts by observing and analyzing the current network state using Equations 5.8 to Equation 5.9. Then it goes into infinite loop. In the loop, it checks if the system state is at the goal state. If so, the algorithm observes and analyzes the next network state. If not, the algorithm invokes $\epsilon-$greedy function to determine the next action to be executed. In ϵ–greedy, the agent selects the highest Q value most of the time (i.e., with probability of $1 - \epsilon$).

The effect of an action is analyzed by observing the new network state and rewarding it as a result. Using this information, the algorithm updates the action-state values and adds this information to the system model.

5.3.5 The Reward Function

The reward signal is used to formalize the learning agent's ultimate goal; steering the network from undesired network operational state to a desired network operational state. The state-action function expressed in Equation 5.11 defines *how good* it is for the learning agent to perform a given action in a given state. As such, the learning agent tries to maximize the *expected* reward value in a long run. Therefore, it is critical to setup a reward value that is truly directing the management system to handle any performance or configuration issues.

The simplest approach is to reward the agent for any transition it makes. However, this may deviate the system from more acceptable state to less acceptable state. Another solution, which has been proposed in [91, 7], is to assign each state with a reward based on the desirability of each state. The desirability of a state is measured by two factors. The first factor is the cumulative weight for each metric involved in that state. The metric's weight is used to indicate its importance. The second factor depends on the current values

Algorithm 4 Adaptive Learning using Dyna-Q

Input: Requirement set $\mathcal{Q}$

$S \leftarrow$ observe current network state
$\langle V, U \rangle \leftarrow analyze(S, \mathcal{Q})$
for ever **do**
    if $\langle V, U \rangle == \langle \phi, \phi \rangle$ **then**
        wait next time event
        $S \leftarrow$ observe current network state
        $\langle V, U \rangle \leftarrow analyze(S, \mathcal{Q})$
        continue
    end if
    $A \leftarrow \epsilon$-greedy(V, U)
    Execute A
    /* *Learning phase* */
    wait next time event
    $S' \leftarrow$ observer current network state
    $R \leftarrow reward(S, S')$
    $Q(S, A) \leftarrow Q(S, A) + \alpha \left[R + \gamma \max_a Q(S', a) - Q(S, A)\right]$
    /* *Planning phase* */
    $M(S, A) \leftarrow R, S'$
    for $i = 1$ to n **do**
        $S \leftarrow$ random previously observed state
        $A \leftarrow$ random action previously taken in S
        $R, S' \leftarrow M(S, A)$
        $Q(S, A) \leftarrow Q(S, A) + \alpha \left[R + \gamma \max_a Q(S', a) - Q(S, A)\right]$
    end for
    $S \leftarrow S'; V \leftarrow V'; U \leftarrow U'$
end for

(or regions) of each metric in the state. Overall, there is a positive value for each state. At first glance, this solution should lead the system to "optimal" behavior. However, we run several experiments using this approach and we realized, in many cases, that the system tries to maximize its reward by revisiting other states before reaching the goal state. We will explain more later.

Our approach for deriving a reward signal is based on the following criteria:

- The main objective of the management system is to find out the best strategy to let the network operates in the highest performance state according to the existing requirements. Therefore, we adopt the work in [7], for which each metric is associated with a weight that expresses the significance of each metric.

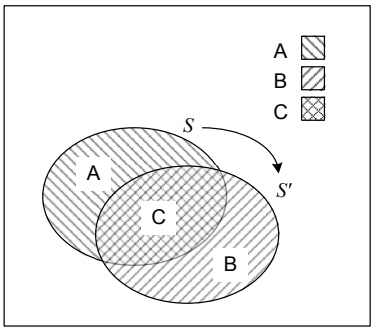


Figure 5.3: The effect of taking an action at state S after which the system will be in state S'

- Figure 5.3 shows the effect of taking action a at state S to transit to a new state S'. Recall that our system state S is expressed in terms of those "unsatisfied" and "unknown" requirements. The effect can be expressed by three regions: region A, region B and region C as shown in Figure 5.3. Region A represents those requirements that have been "satisfied" after taking action a. Region C represents those requirements that were violated at state S and still violated after taking taking a. Region B represents those requirements that were violated after taking action a. Thus, the reward function should lead the system to maximize region A and avoid generating region B.

- We need to maximize region A in a few steps as possible.

Based on the above observation, we propose the following reward function. Instead of assigning a positive reward as in [91], we assign a negative reward. Any action that leads to the final goal will get a reward of zero. This means that our reward is actually a penalty where the penalty is reduced as the system moves to the goal state. Therefore, our objective is to minimize the cumulative penalty as we shift the system to the goal state. This implies that we consider regions B and C, which represent state S'. Hence the reward received at state S is the penalty of being at state S', which can be expressed as

$$R = -100 \times \left[\alpha \sum_{q \in \mathcal{Q}_v} \frac{weight(q)}{W} + (1 - \alpha) \sum_{q \in \mathcal{Q}_u} \frac{weight(q)}{W} \right] \tag{5.12}$$

	a1	a2	a3
S1	22.22	21,22	19,78
S2	22.78	10	19.78
S3	22.78	17.98	19.78
S4	10	17.89	22.22
S5	10	10	21.22

Table 5.2: Optimal policy with positive rewards in each state

where $weight(q)$ is the weight of the metric in requirement q and W is the total sum of all weights.

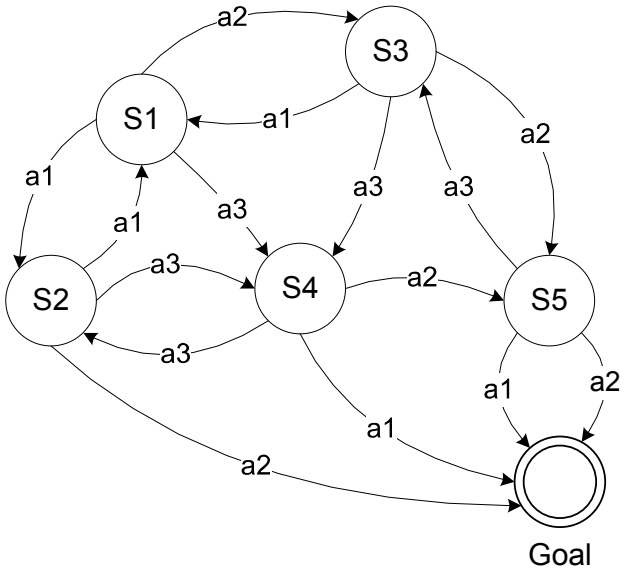


Figure 5.4: A sample of state–transition diagram

In order to confirm the efficiency of the reward function, we experimented with a computer simulation. We considered a deterministic state–transition diagram as shown in Figure 5.4. The diagram consists of five states and one goal state. Each state has three actions labeled as $a1$, $a2$ and $a3$. There are several loops in the diagram to harden the learning process.

In our first experiment, we assigned each state a positive reward to indicate its desirability. We considered the following rewards: $R(S1) = 5, R(S2) = 4, R(S3) = 3, R(S4) = 2, R(S5) = 1,$ and $R(G) = 10$. We ran standard Q-learing algorithm using ϵ-greedy algorithm where $\epsilon = 0.1$. The optimal Q values (i.e., optimal policy) is shown in Table 5.2.

	a1	a2	a3
S1	-2	-5	-4
S2	-2.6	0	-4
S3	-2.6	-5	-4
S4	0	-5	-2
S5	0	0	-5

Table 5.3: Optimal policy with negative rewards, in each state

As expected, the system has visited as many states as possible to collect more rewards. The optimal actions got less Q–values. We also noticed that the agent took long time to reach the optimal policy.

In the second experiment, we assigned each state a negative reward to indicate its undesirability. We considered the following rewards (with the same degree of desirability in the first experiment): $R(S1) = -1, R(S2) = -2, R(S3) = -3, R(S4) = -4, R(S5) = -5$, and $R(G) = 0$. The optimal Q values are shown in Table 5.3. The agent successfully obtained the optimal configuration. For example, if the system is in state $S1$, the system has two shortest paths to reach the final goal: $S1 \rightarrow S2 \rightarrow G$ or $S1 \rightarrow S4 \rightarrow G$. However, moving to state $S4$ is more *undesirable* than moving to state $S2$. So, the agent successfully learned the right Q values.

5.4 Summary

Automating network configuration is a challenging topic in networking research. One of the major problem in network configuration is how to maintain reachability, security and performance requirements. We designed a configuration management system not only to automate service configuration but also to adapt its configuration to fulfill high–level requirements. We adopted policy–based management for automation and adaptation. Sometimes the network administrator has multiple choices to handle QoS conflicts. To enable our management system to figure out the best choice, we implemented Dyna-Q algorithm, which is a Q-learning technique that allows the system to learn on–line. We also presented a novel formalization for

modeling configuration and expectation policies in order to have a compact representation and to enable us to use Dyna-Q with large–sized networks.

Chapter 6

Implementation

AutoConf system is mainly implemented using the Erlang language along with C programs that are linked to the Erlang Subsystem. In this chapter, we provide a brief overview of the Erlang language and we then present in detail the overall architecture of the AutoConf system. Since AutoConf relies on the SCL language, we also present the SCL grammar. Finally, we discuss the implementation of network configuration change, network configuration verification and network configuration automation.

6.1 Erlang Language

Erlang [3] is a concurrent functional programming language that supports real-time and fault-tolerance distributed systems. It has been used in writing many critical applications such as the AXD 301 ATM switch[1] [13].

An Erlang program consists of a set of modules. Each module basically contains a list of function definitions. Each function consists of a set of Erlang expressions. A function, which has a name *fun_name* defined in the module *mod_name* with arity N, is often denoted as *mod_name:fun_name/N*. List 6 shows a sample Erlang module called `echo` which exports

[1]The software was consisting of over half a million lines of Erlang code.

two functions: `start`/0 and `loop`/0. The function `start`/0 spawns a new process which will be responsible to execute `echo:loop/0` function in *parallel* with the calling function. Each process has a message queue to store the incoming messages. Erlang has asynchronous communication mechanism where any process can send a message to any other process by using `!` operator. The later process can inspect its mailbox by the `receive` statement. A sequence of patterns can be specified to read specific messages from the mailbox. When reading a message, a process is suspended until a matching message arrives or timeout occurs.

Erlang language has a huge library called OTP (Open Telecom Platform). OTP is a programming platform that provides ready–to–use components (libraries) and services such as:

- Distributed database system called Mnesia. Mnesia was designed to provide concurrent, soft real–time system with high–availability requirement. It supports database transactions, data indexing, and relational queries.

- Fast key–value lookups of potentially complex data [31].

- Efficient set of algorithms for directed graph and directed acyclic graph (DAG).

```
-module(echo).
-export([start/0, loop/0]).

start() ->
   spawn(echo, loop, []).

loop() ->
   receive
        {From, Message} ->
            From ! Message,
            loop()
   end.
```

List 6: Erlang module

- XML, SSH and encryption libraries that can be used to implement NETCONF protocol at client side.
- An LALR-1 parser generator for Erlang called `yecc` similar to `yacc`.
- Port driver that links Erlang program with other programs written in different languages such as C, C++ and Java.

For more information about the language, the reader may refer to [3].

6.2 Overall Architecture

The overall architecture of AutoConf system utilizing our proposed framework, as described in section 3.2, is depicted in Figure 6.1. Network administrators perform device configuration by accessing SCL-enabled console manager. The console manager provides interactive text-based interface to read manager commands or SCL files to be executed. While executing commands, the console manager may require to query Domain Knowledge Base (DKB) to retrieve some specific CSM predicates.

AutoConf is a fault-tolerant system since it is expected to run forever. AutoConf application consists mainly of AutoConf Supervisor, SSH engine, and Database Engine. AutoConf supervisor is responsible to launch and monitor BDD processes, policy engine and Device Supervisor. BDD processes are responsible to run an exteranl BDD package and link that package with the Erlang system. A BDD package is linked to the Erlang system using Erlang port interface instead of dynamically linked into the Erlang system. Although dynamic linkage is the fastest way of calling C functions from Erlang, it is least safe because a crash in BDD package brings AutoConf down too.

Device Supervisor is responsible to launch and monitor the device manager and a set of device processes. Each device process is associated with a physical network device, and when it launches, it tries to establish a persistent NETCONF session with that physical

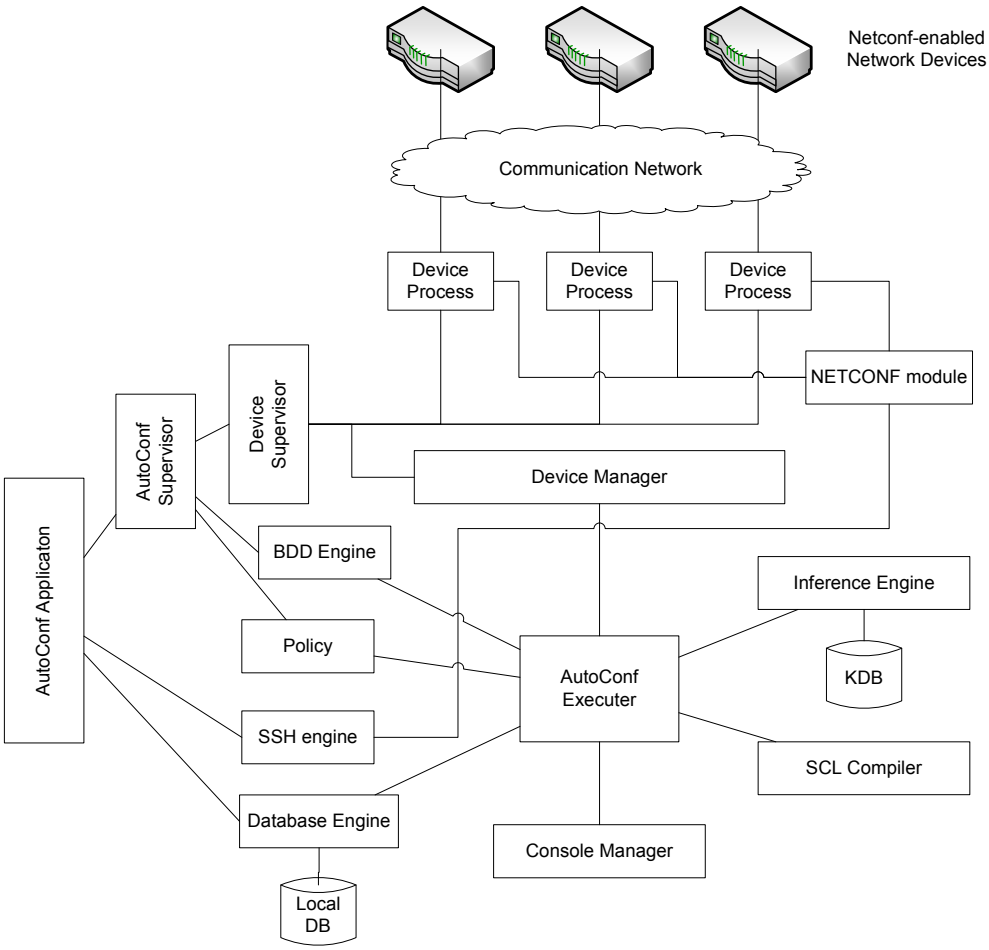


Figure 6.1: AutoConf management architecture

device. To enable AutoConf to communicate to all managed devices at once, it is expected that all managed devices have the same authentication information, and therefore the device supervisor prompts for password authentication only once and uses that password to authenticate with all NETCONF-enabled network devices. If a device process is killed due to a connection loss between AutoConf and a physical network device, the device supervisor keeps trying to connect to that device for a period of one hour before it gives up.

Policy engine is responsible to handle network requirements as well as network states received from a monitor subsystem (not shown in the figure). Policy actions, which are required to be executed, are sent to the AutoConf executer. It is worth mentioning that the policy engine acts as a policy decision point (PDP) as described in IETF COPS architecture

(RFC 3198). The device manager acts as a policy enforcement point (PEP), while device processes act as effectors (E's).

All engines are linked to the AutoConf executer. AutoConf Executer is a set of Erlang modules to performs severals tasks. One task is to execute the user commands. Another task is to provide a unified interface to the database engine.

Figure 6.2 shows process hierarchy of AutoConf application in the Erlang system. AutoConf application runs Mnesia, Crypto, and SSH applications as shown on the left–hand side. AutoConf's main process has process ID (PID) $< 0.38.0 >$ and creates a control process with PID $< 0.39.0 >$. This control process creates Autoconf supervisor(autoconf_sup) which, in turn, creates two BDD engines buddy and rsm, policy engine and device supervisor (device_sup) engine. As shown, there are four device processes: rtr01, rtr02, rtr03 and rtr04. Each device process establishes a persistent NETCONF session with its associated network device. Notice that the name of a device process is the same name as in CSM's device concept.

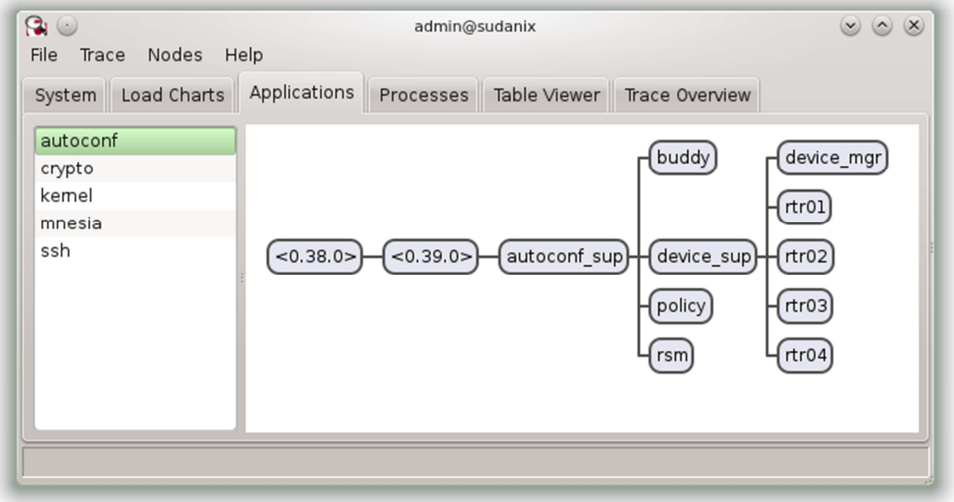


Figure 6.2: AutoConf Application running in Erlang system

The architecture involves different kind of users to build NETCONF-enabled automated system. One user is responsible to write the appropriate data models for the network

devices. Data models are considered as a set of contracts between a NETCONF server and a manager that both endpoints must adhere to the syntax and semantic of the modeled data. Another user is a domain expert who writes configuration specifications for network services. These specifications will be stored in the DKB database. A third user is responsible to encode policy rules. Last user is network operator who uses the specifications stored in local repository to write SCL commands.

6.3 SCL Grammar

SCL compiler as shown in Figure 6.1 consists of SCL lexical analyzer and SCL parser. SCL lexical analyzer is generated by using Erlang `leex` module, while SCL parser is generated by using Erlang `yecc` module. For Erlang `leex` module to generate SCL lexical analyzer, it takes as arguments a list of regular expressions that describes all tokens in SCL language. While Erlang `yecc` takes as argument an SCL grammar that supports LALR(1) technique to generate an SCL parser.

SCL grammar is written using Backus-Naur Form or BNF as shown in List 7. As we mentioned, the grammar file is given to the Erlang `yecc` module to generate SCL parser. SCL parser is then responsible to compile SCL files and generate Erlang codes. Generated Erlang codes are then given to the AutoConf executer engine in order to be executed.

6.4 Configuration Change Implementation

In SCL, configuration operations are performed by using `manage` command. Autoconf executes `manage` command as follows:

1. It determines a list of YANG modules involved (which are basically determined by service name and root node names).

2. It determines a list of devices involved in the command.

3. It sends these lists to the device manager.

4. The device manager distributes generated uncompleted-NETCONF command to each device process in the list.

5. Each device process adds appropriate RPC header, sends the completed–NETCONF commands, and waits for RPC reply.

6. Each device forwards its reply back to the device manager.

7. The device manager collects all expected replies and sends back to the AutoConf executer.

8. The AutoConf executer analyzes the result and displays the final result via console manager.

When configuring multiple devices, the `manage` command will be executed by device processes in parallel. The advantage of having parallel processing is to speed up configuration process and hence enabling network services in very short time. The disadvantage is that it may create congestion in the network. As indicated [100], NETCONF messages consumes more bandwidth than SNMP due to verbosity and self–descriptive of XML documents. One

```
%%
%% SCL COMMANDS
%%
scl_command_list ->
    scl_command scl_command_list : ['$1' | '$2'].
scl_command_list ->
    scl_command : ['$1'].

scl_command -> manage_command    : '$1'.
scl_command -> foreach_command   : '$1'.
scl_command -> policy_command    : '$1'.
scl_command -> verify_command    : '$1'.
scl_command -> eval_command      : '$1'.
```

List 7: An excerpt of SCL grammar in Erlang–BNF notation

solution is to encapsulate `manage` with `foreach` command so that it iterates over devices. In this case, `foreach` produces a series of `manage` commands that will be executed sequentially.

6.5 Configuration Verification Implementation

Configuration verification as mentioned in section 4.4 relies on a formal model, which is BDD. In our implementation, we use 104 bits to encode the packet header plus 8 bits to encode the action field. In case of routing policy and firewall policy, the action field is used to encode a device interface. This implies that the maximum of number of interfaces is 128 (since one bit is used for direction).

In SCL, a verification rule is represented by using either `policy` or `verify` commands. The execution path of these commands is similar to the `manage` command as described in the previous section.

6.6 Configuration Automation Implementation

Configuration Automation is implemented inside the policy engine. This engine uses RSM (Requirement and State BDD Module) engine to encode requirements and network states. All equations discussed in Chapter 5 use 20 bits to encode Requirement ID, 45 bits to encode metric specification (target name + service name + metric name), 64 bits to encode value range and one bit to encode value type (0 numberic value, 1 IP address). Thus, the total number of bits is 130 bits.

The policy engine is acting like an event-handler server. It waits for an event either from a monitor or from a timer, to begin its management cycle. In this cycle, the engine performs Algorithm 4 (as described in Chapter 5). If it decides to execute an action, then it will send a notification to AutoConf Executer to run SCL function. The notification carries the SCL function name along with a list of arguments.

6.7 Summary

In this chapter, we present an overview of the overall architecture of AutoConf system. Then we present how we developed the SCL language. Finally, we shed some lights on how AutoConf performs configuration operations, verification, and automation.

Chapter 7

Experimental and Evaluation Results

This chapter presents a set of experiments to evaluate AutoConf flexibility and its performance. To evaluate its scalability, we run a set of simulations with different network sizes.

7.1 Experimental Setup

The setup of our experiments consists of a hypervisor machine running VMware ESXi version 4.1. The machine that hosts the VMware is equipped with an Intel Pentium dual-core CPU running at 2.8 GHz, a memory RAM of size 4GB, and two SATA hard-drives. On the top of VMware's hypervisor, there are seven virtual machines each running CentOS 6.2 with Linux kernel 2.6.32. Four virtual machines are acting as routers. The routing software installed in these machines is Quagga version 0.99. Quagga supports most IP routing protocols such RIPv1, RIPv2, OSPF, and BGP. Two virtual machines are used as two end hosts. And the last one is used as an administrator machine which runs our tool AutoConf.

AutoConf assumes that managed devices are implementing NETCONF protocol and YANG data model (RFCs 4741, 6241 and 6020). There are several tools that supports NETCONF protocol. Throughout our dissertation, we investigated three tools: EnSuite,

ConfD and Yuma NETCONF server.

EnSuite [59], ConfD [86] and Yuma [102] are network management suits. They consists of a NETCONF agent (or NETCONF server), a NETCONF manager and a set of extension libraries and utilities such as YANG parser. The followings give a brief description for each suite.

EnSuite is an open source framework implemented in Python. It consists of YencaP server (NETCONF agent), YencaP manager and YANG parser called jYANG. YencaP server is an extensible server compliant to NETCONF protocol 1.0. YencaP manager is a NETCONF client application that sends queries and receives responses with any NETCONF-compliant server. It acts as HTTPS server where a user can establish HTTPS sessions. There is a one to one mapping between HTTPS and NETCONF sessions. Once an HTTPS session is established and subsequently connected to NETCONF Server, YencaP displays the management information in graphical interface (as Java Applet) supported by that server in a tree structure fashion. A user can navigate through the tree and perform GET and SET operations, where permissible, on any node in the tree.

There are several disadvantages of YencaP server. First, it has a limited support for the NETCONF protocol. It does not support NETCONF protocol 1.1, NETCONF notifications, and partial locks. Second, the last updated version was published in 2010 before standardizing the YANG data model. Thus, jYang is based on a draft version. Third, our experimental data shows that YencaP does not check the correctness of the uploaded data. In other words, YencaP does not automatically check the configuration data sent by a manager.

ConfD is a commercial framework developed by Tail-f that implements the NETCONF protocol and YANG data model. ConfD is basically a management platform that can be installed on managed devices and run as a regular Unix daemon. ConfD can act as a NETCONF server, an SNMP agent, a Web server or as CLI. It also contains a built-in XML configuration database.

In ConfD, each managed object (such network interfaces, DNS service, or OSPF service) is associated with a software application that binds YANG content to the managed object. This software, which runs as a regular UNIX daemon, implements the specific behavior as defined by the YANG module statements. ConfD process and managed object processes are connected via TCP/IP Socket interface. Moreover, ConfD allows NETCONF managers to send NETCONF messages via TCP without SSH. This is a very useful feature for agent developers to easily debug the software and trace the packets exchanged between ConfD and NETCONF managers.

Yuma initially was an open source framework implemented in C language. The last version developed as an open source was 2.2.5. It consists of netconfd (NETCONF server), yangcli (NETCONF client) and YANG parser called pYang. In the following paragraphs, we provide detailed differences between Yuma and ConfD

- ConfD and Yuma have different architectures. As we mentioned, there is a dedicated process called "Confd" that implements the NETCONF protocol at the server side. Each agent software is a separate process that communicates to "confd" using TCP sockets. Yuma server is always a single process because the agent software is linked to the NETCONF server as a shared library. Therefore, Yuma server is more efficient than ConfD in terms of performance. However, ConfD is more reliable than Yuma, because if an agent software has crashed due to bugs in coding, only the agent process would be crashed. It would not affect the ConfD process and the other agent processes. In Yuma, if the agent software has crashed, the whole process would be collapsed.

- Both Yuma and ConfD servers can be tuned and configured by editing their configuration files. ConfD configuration file is an XML file, while Yuma configuration file is a YANG file. Eventually, Yuma has been developed based on YANG technology. All features are added as YANG module, including NETCONF protocol description itself. This makes Yuma package more flexible and extensible than ConfD.

- Before running Yuma NETCONF server, all shared libraries (agent programs) should be stored in a specific directory as well as their YANG data models. The server checks these directories and loads these shared libraries automatically. A manager can load a shared library manually without shutting down the server. In ConfD, the ConfD process should be executed first, then other agent processes can be executed individually.

- Both Yuma and ConfD support Command-Line Interface to manage agents. They both supports auto-completion feature like Cisco CLI. In Yuma, the manager must first establish NETCONF session using connect command. Then CLI provides a set of commands to query, create, modify, and delete configuration variables. Based on our empirical work with Yuma NETCONF client, a manager cannot send an XML document to the NETCONF server as in ConfD package. Moreover, ConfD has the capability to auto-generate a web site to build a web-based interface as an alternative north-bound interface.

- Yuma and ConfD suites provide a set of API to help agent developer to bind YANG content with managed object content. In Yuma, the API is a set of C functions, while in ConfD the API is written in C and Java. Yuma provides a very useful tool to generate a template software tailored based on YANG modules. This will eventually reduce the developing time dramatically. On the other hand, ConfD requires some modifications to YANG modules in order for agent software to be able to handle YANG contents.

The last open source version of Yuma was 2.2.5. This version supports NETCONF protocol 1.0 and 1.1, all NETCONF standard capabilities (like confirm, validate, xpath, etc), YANG data model, and NETCONF notification. The last version of ConfD that has been installed in our research lab was ConfD 2.9. This version supports only NETCONF 1.0. For this reason, we installed in all our experimental devices Yuma basic version 2.2.5.

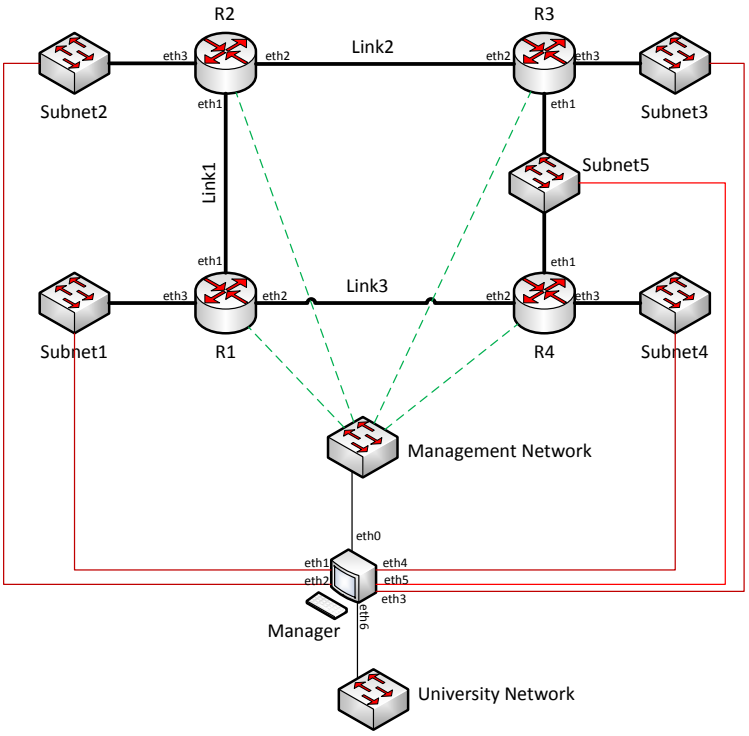


Figure 7.1: Experimatal Network setup

Our network setup is shown in Figure 7.1. The network consists of five subnetworks (subnet1 to subnet5) as well as a management subnetwork. To simplify the network diagram, we did not show the end hosts; however, the connectivity of end hosts is similar to the manager machine except that they are not connected to the university network. Each router or end host is connected to the management subnetwork (subnet address 10.1.1.0/24) via the pre-configured interface `eth0`.

7.2 Basic Configuration Scenarios

In this section, we show how to configure the above network using AutoConf system. We start by configuring the network interfaces, then we implement different configuration scenarios.

As we mentioned in the previous section, `netconfd` is a generic server that handles all aspects of the NETCONF protocol operations. However, it does not understand the semantic

of YANG modules (for example, how to enable a network interface). Yuma suite generates a set of callback functions (a callback function for each data element in YANG module) that binds YANG content (managed by the netconfd server), to the network device. These functions implement the specific behavior, as defined in YANG module statements. As a result, for each configuration scenario we wrote a YANG module along with its semantic implementation. Our code is then compiled as a shared library and made available to the netconfd server. YANG modules are provided in Appendix A.

7.2.1 Topology specification

As we mentioned in section 3.3, topology specification describes the network topology to AutoConf system in a systematic way and provides its capabilities (which services it should handle). The following shows the complete topology specification to the network in Figure 7.1.

```
/* define our network domain */
{device, cans, undefined, [network]},

/* define all devices in network cans */
{device, r1, cans, [router, linux]}, {device, r2, cans, [router, linux]},
{device, r3, cans, [router, linux]}, {device, r4, cans, [router, linux]},

{device, s1, cans, [subnetwork]}, {device, s2, cans, [subnetwork]},
{device, s3, cans, [subnetwork]}, {device, s4, cans, [subnetwork]},
{device, s5, cans, [subnetwork]},

{device, host1, cans, [host, linux]}, {device, host2, cans, [host, linux]},

/* link definitions -- we just show for R1 */
{link, serial, [{r1, eth1}, {r2, eth1}], []},
{link, serial, [{r1, eth2}, {r4, eth2}], []},
```

Subnet	Address	Subnet	Address
subnet1	192.168.1.0/24	subnet5	192.168.5.0/24
subnet2	192.168.2.0/24	link1	192.168.10.0/30
subnet3	192.168.3.0/24	link2	192.168.10.4/30
subnet4	192.168.4.0/24	link3	192.168.10.8/30

Table 7.1: IP Subnet Plan

```
{link, ethernet, [{r1, eth3}, {s1, 1}], []},

/* define network services */
{service, rip, [routing]}, {service, ospf, [routing]}, {service, interface, [link]},
{service, bridge, [bridge]}, {service, system, [os]},

/* Data modules */
{data, system, yang, 'yuma-system'}, {data, interface, yang, interfaces},
{data, rip, yang, 'routing-rip'}, {data, ospf, yang, 'routing-ospf'},
{data, bridge, yang, bridges},

/* NETCONF mangement agents */
{agent, r1, "10.1.1.1", ssh, 830}, {agent, r2, "10.1.1.2", ssh, 830},
{agent, r3, "10.1.1.3", ssh, 830}, {agent, r4, "10.1.1.4", ssh, 830},
{agent, host1, "10.1.1.101", ssh, 830}, {agent, host2, "10.1.1.102", ssh, 830}
```

7.2.2 Interface configuration

As usual in network configuration process, a network administrator starts by designing a subnetworking IP plan. In this design, the allocated IP address space is distributed among subnetworks. Let us consider the following subnetwork plan as depicted in Table 7.1.

SCL allows the administrator to define the subnetworks by using `sequence` construct. The following lines show how to define subnetworks `subnet1` and `link1` using `sequence`

construct:

```
sequence subnet1:ip {192.168.1.0, 24}
sequence link1:ip {192.168.10.0, 30}
```

To express the interface configuration semantically, we define a new CSM concept called **ifconfig**. The schema of this concept is:

```
schema ifconfig {device, interface, ip, mask}
```

After that we define an `ifconfig` *semantic* view for each interface using the sequence generator defined previously. For example, to define `ifconfig` for device R1 semantically:

```
{ifconfig, r1, eth3, seq:next(subnet1), seq:prefix(subnet1)}
{ifconfig, r1, eth1, seq:next(link1), seq:prefix(link1)}
{ifconfig, r1, eth2, seq:next(link3), seq:prefix(link3)}
```

The function **seq:next()** automatically generates a new IP address within the subnetwork that is specified as argument. The function **seq:prefix()** returns the network prefix value.

After defining the configuration of all network interfaces, AutoConf takes the specification and generates an actual IP address plan as shown in Figure 7.2.

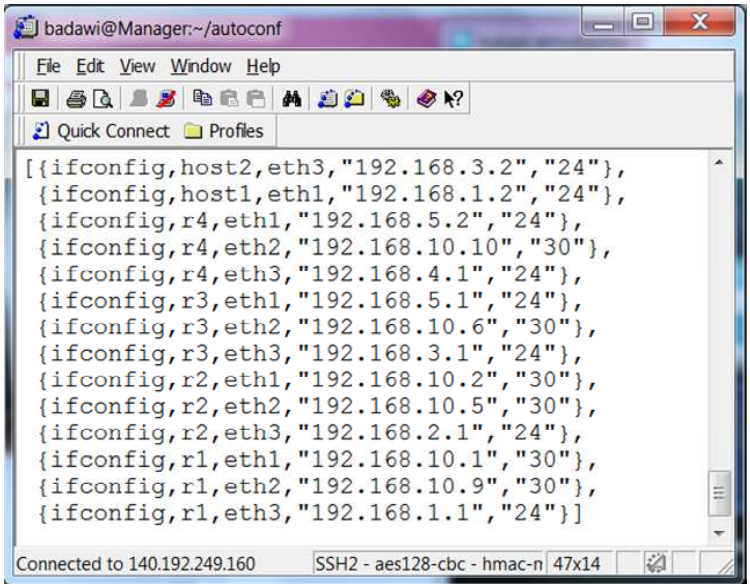


Figure 7.2: Interface configuration as generated by AutoConf Executer

The final step in interface configuration is to apply this specification on network devices using NETCONF protocol. The SCL manage command to configure network interfaces is:

```
manage cans:interface {
    config running { /* configure running database */
        set interfaces {
            foreach ifconfig (.device == #device.name) {
                set interface {
                    set name = .interface;
                    create inet/address = .ip ++ "/" ++ .mask;
                    set up = true;
                }
            }}}}
```

The meaning of the above command is as follows. Manage all devices in network "`cans`" that has *interface* service. For each device $X \in domain(cans)$, configure its "`running`" datastore. Under `running` datastore, select "`interfaces`" data element. The NETCONF command `set interface` will be repeated based on the number of `ifconfig` predicates that belongs to device X. Within interface container, we set up name, inet/address and up parameters. Please note that the data definition of `address` in YANG module is `ipprefix` (i.e. IP address in CIDR notation). As we can see, the administrator writes a single command to configure a set of devices. This ensures the consistency of configuration between multiple devices.

7.2.2.1 Validating Interface Configuration

There are two configuration parameters that need to be checked: interface status: up or down (represented in YANG module as a Boolean variable called up) and interface address (represented in YANG module as ipprefix variable called address). Therefore, we define a set of verification rules based on these parameters.

Rule 1: *All configured interfaces are up.* Before formalizing this rule, let us consider a simple scenario where we need to ensure that the interface "eth1" in routers: r1, r2, r3, and r4 is up. This can be verified by using the following rule:

```
verify [r1, r2, r3, r4]:interface {
    content {
        ifs: "/interfaces/interface[name='eth1']/up";
    }
    assert all : X == "true";
}
```

If the output of the above rule is "true", then it implies interface 'eth1' on routers r1, r2, r3 and r4 is up. Please note that the XPath expression always returns string values. Therefore, we compared X with the string "true".

Now to check all configured interfaces, we utilize the interface configuration specification (i.e. "ifconfig"). The rule can be formalized as follows:

```
eval all {
    foreach ifconfig {
        verify .device:interface {
            content {
                ifs: "/interfaces/interface[name='" ++ .interface ++ "']/up";
            }
            assert all : X == "true";
        }}}
```

The construct **foreach** iterates over all "ifconfig" predicates. For each predicate a **verify** construct will be executed. The special variable .device will be replaced with #ifconfig.device element (please recall ifconfig schema) and the variable .interface will be replaced with #ifconfig.interface. The collection of all verification rules will be evaluated by using **eval** construct.

Rule 2: *IP address of each network interface matches the subnet plan.* This rule can be simply formalized as follows:

```
verify r1:interface {
    content {
        ifs: "/interfaces/interface[name='eth3']/inet/address;
    }
    assert all : network(X, seq:prefix(subnet1)) == seq:network(subnet1);
}
```

The function **network()** takes as argument an IP address in CIDR notation and network prefix, and returns the network address. The sequence function **network()** returns the network address of the sequence element.

Rule 3: *no non-equal interfaces are placed on the same IP subnet*. This rule can be formalized by using "list" construct instead of "content". Therefore, the rule is:

```
verify cans:interface {
    list {
        ifs: "/interfaces/interface/inet/address";
    }
    assert all : distinct(network(X));
}
```

7.2.3 RIP configuration

In this section, we demonstrate two examples. In the first example, we show how to configure protocol–specific parameters on all routers. The second example shows how to enable RIP protocol without defining a new CSM configuration specification.

Based on RIP data structure, the command below enables RIP protocol and sets up the RIP version to 2 on all routers under LAN "cans".

```
manage cans:rip {
   config running {
       create rip {
           set version = 2;
```

```
    }}}
```

Notice that enabling RIP protocol is performed by *creating* "rip" data element. Within "rip", we set rip version to 2. To disable RIP protocol, we just delete "rip" data element as follows:

```
manage cans:rip {
   config running {
       delete rip;
   }}
```

The next example shows how to add network "192.168.5.0/24" to R3 and R4:

```
manage [r3, r4]:rip {
    config running { // config running datastore
        set rip {
            create network = seq:network(subnet5) ++ "/" ++ seq:prefix(subnet5);
        }
    }}
```

Please note that Quagga software requires network prefix in order to add a network.

7.2.3.1 Validating RIP configuration

It is necessary to guarantee that all routers are configured consistently. For example, we would like to ensure that all routers are configured with the same RIP timers or all are running on the same RIP version.

Rule 1: All routers are running RIP version 2. The following rule validates that all routers are running the same RIP version:

```
verify cans:rip {
    content {
        rip : "/rip/version";
    }
```

```
    assert all : int(X) == 2;
}
```

The function **int()** coverts the string X to an integer value. Of course, we can write "assert" expression in the same way as we did in interface validation, we just like to demonstrate the richness of SCL language.

Rule 2: Each router must advertise at least 2 networks. This rule can be formalized by counting the number `network` element under `rip` container:

```
verify cans:rip {
    list {
        rip : "/rip/network";
    }
    assert all : count(X) >= 2;
}
```

Rule 3: All routers are configured with the same RIP update timer. This rule can be achieved by collecting update timer from all routers, and then we check for similarity by using `similar()` function. The following rule illustrates the process:

```
verify cans:rip {
    list {
        rip : "/rip/timers/update";
    }
    assert all : similar(X);
}
```

7.2.4 OSPF configuration

In this scenario, we show only without validation the configuration of OSPF protocol using user–defined CSM concept. The purpose of this concept is to inter–relate between link attributes since OSPF is a link–state protocol.

In this study, we consider the following attributes of a link state: network address, network prefix, area number, and directly connected routers (we ignore other attributes such as link cost). Consequently, we define a new schema called **ospflink** that composes of address (network address), mask (network prefix), area, devices (directly connected devices). The following shows the schema definition in SCL along with high–level configuration specifications.

```
/* ospflink concept */
schema  ospflink {address, mask, area, devices}
/* high-level configuration */
insert {
    {ospflink, seq:network(subnet1), seq:prefix(subnet1), 0, [r1]},
    {ospflink, seq:network(subnet2), seq:prefix(subnet2), 0, [r1]},
    {ospflink, seq:network(link1),   seq:prefix(link1),   0, [r1, r2]},
    {ospflink, seq:network(link2),   seq:prefix(link2),   0, [r2, r3]},
    {ospflink, seq:network(link3),   seq:prefix(link3),   5, [r1, r4]},
    {ospflink, seq:network(subnet3), seq:prefix(subnet3), 5, [r3]},
    {ospflink, seq:network(subnet4), seq:prefix(subnet4), 5, [r4]},
    {ospflink, seq:network(subnet5), seq:prefix(subnet5), 5, [r3, r4]}
}
```

As noticed, the manager decided to divide the network into two areas: 0 and 5 as shown in Figure 7.3. Expressing network configuration in high–level abstraction simplifies configuration process and reduces misconfiguration errors.

Afterwards, the manager can write an SCL command to produce consistent multi-device configuration:

```
manage cans:ospf {  // manage all devices support OSPF in cans
    config running {
        foreach ospflink (#device.name in .devices) {
            create ospf/network {
                set prefix = .address ++ "/" ++ .mask;
                set area = .area;
            }
```

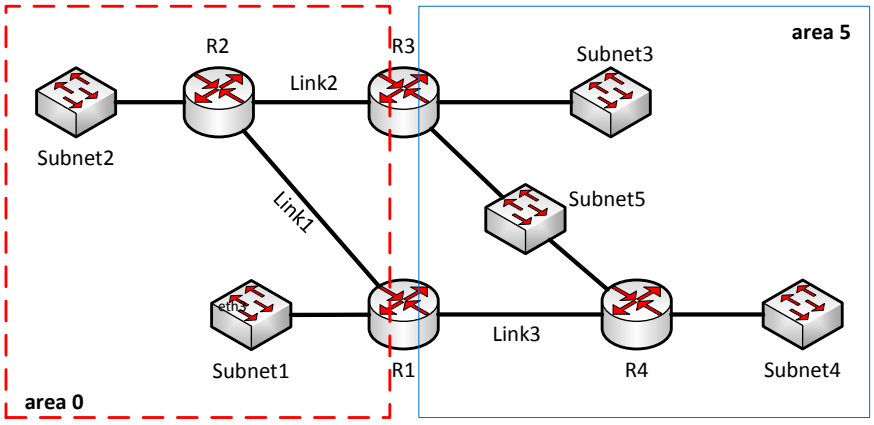


Figure 7.3: OSPF links setup

```
}}}
```

Notice that `foreach` statement iterates over all predicates of type `ospflink` that satisfy the condition between parenthesis, and executes the inner statement. In large-scale networks, we can partition the devices into a set of sub-domains. Then each remote AutoConf can query the distributed database to produce the configuration messages that are related to its sub-domain.

7.2.5 MPLS VPN Configuration

This study demonstrates the scenario of activating MPLS Layer 3 VPN in service provider networks for customers. The feature of MPLS VPN is that it allows several sites to interconnect transparently through service provider's network. Within a VPN, each site can send IP packets to any other site in the same VPN.

In this scenario, we are going to use the network topology depicted in Figure 7.4 where routers `r4` and `r5` are Customer Edge (CE) routers, and routers `r2` and `r3` are Provider Edge (PE) routers. Before proceeding, we assume that OSPF protocol and MPLS have been already configured in the ISP network.

Configuring MPLS VPN requires three steps. The first step is the configuration of *virtual routing and forwarding* (VRF) table as well as a set of interfaces that use this VRF entry at

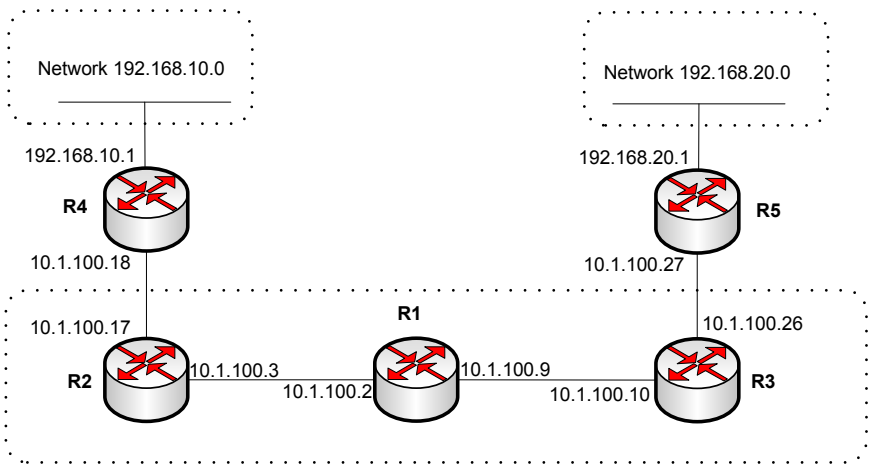


Figure 7.4: Customer wants to link its two Sites (Site1 and Site2)

the PE routers. The second step is the configuration of PE routers to use Multiprotocol BGP (MP-BGP) to distribute VPN routing information using MP-BGP extended community. The third step is the configuration required to implement PE-CE routing sessions which is depending on the PE-CE routing protocol (e.g. static, RIP, OSPF, etc).

The service provider's IT team initially designs the set of concepts that describe the MPLS-VPN service. Let us assume that the description has the following concepts: `vpnform`, `vpnspec`, `vpn_if`. The concept `vpnform` stores the details of the agreement between the service provider and the customer. The concept `vpnspec` describes the configuration specification to provision a new VPN. The concept `vpn_if` describes which interfaces are facing customer CE routers. In addition, a domain expert in MPLS VPN configuration is responsible of writing the SCL code to construct the appropriate NETCONF messages based on the concepts defined above.

When a customer requests a VPN service, he/she fills an appropriate provisioning form. The form will be forwarded to IT department to initiate the service deployment. A network operator uses the submitted form and inserts new predicates to the system. The following script shows the high-level specification of MPLS VPN provisioning request:

```
insert {
   /* custID 100 with bandwidth of 512 */
```

```
   {vpnform,"XYZ company",100,"192.168.0.0",512},
   /* vpn name is red with RD 100:1 */
   {vpnspec, 100, "red", "100:1", [r3, r4]},
   /* specifications for interfaces */
   {vpn_if, "red", r3, "fa0/1", "192.168.1.1", 24},
   {vpn_if, "red", r4, "fa0/1", "192.168.2.1", 24}
}
```

Once the above specification has been inserted, the operator only needs to run the SCL code to generate the NETCONF messages that will be sent to NETCONF servers. The configuration actually requires several data modules such as VPN MPLS data module, MP-BGP data module and routing protocol modules. Due to lack of space, we only consider the configuration of VPN MPLS data module, even without listing the detail of the data definition.

```
foreach vpnform (.custid = CUSID) {
   foreach vpnspec (.id = #vpnform.custid) {
      manage vpnspec.pe:mplsl3vpn {
         config running {
            set vrf {
               set name = #vpnspec.name;
               set rd = #vpnspec.rd;
               set 'vrf-routing' {
                  set policy = "import";
                  set policy = "export";
               }
            }
            foreach vpn_if (.name = #vpnspec.name and
                  .router = #device.name) {
               create interface {
                  set name = #vpn_if.interface;
                  set address = #vpn_if.address;
```

```
                set mask = #vpn_if.mask;
                set 'vrf-forwarding' = #vpn_if.name;
            }
        }
    }
}}}
```

When the above code is executed, the management system will prompt the user to enter the customer ID. Thus, the complexity of provisioning a new service has been reduced by translating the high-level requirement documented in the customer's form to a set of predicates.

As indicated above, the main merit of our framework is that it allows different users to build up service configuration. A network manager, for example, is responsible to define the concepts needed to specify the configuration. A domain expert is responsible to codify the specification using SCL language. A network operator uses the defined concepts to create a set of specifications (based on the guidance of the manager) and executes the appropriate SCL modules.

7.2.6 Automating interface configuration

We start demonstrating the automation feature in AutoConf management system. First, we present the interface requirements to automate them. The policy rule specification can be expressed as follows:

```
For any device X in CANS, if  X:interface:Y is not enabled then call ifconfig(X, Y)
```

The above policy rule can be translated to generate 14 requirements based on our topology specification:

```
{101, host1, interface, eth1, 1, [ifconfig(host1, eth1)]}
{102, host2, interface, eth1, 1, [ifconfig(host2, eth1)]}
{103, r1, interface, eth1, 1, [ifconfig(r1, eth1)]}
.
```

```
.
{114, r4, interface, eth3, 1, [ifconfig(r4, eth3)]}
```

When an interface or a link is down, the monitor system should report this incident to AutoConf using NETCONF notification or SNMP protocol. We manually inserted this notification to AutoConf system. When AutoConf receives that an interface is down, it will perform the following actions: (1) updating the system state (2) triggering (by policy engine) "`ifconfig`" action to configure the interface at each management cycle, and (3) updating the new system state when "ifconfig" returns successfully. Note that the Q value of "ifconfig" will not be incurred when "ifconfig" returns unsuccessfully.

7.2.7 Automating Filtering policy

Now we consider the problem that has been raised in [34]. In this scenario we are going to run a simulation to examine the behavior of AutoConf to resolve the conflict. The simulation considers the network topology in Figure 7.1 without link1. The manager defines the following requirement: Any host in Subnet4 should NOT communicate with any server in Subnet2. This requirement can be formalized as

```
{201, network, path, check1, 1, [insert_filter("192.168.4.0/24", deny, R2),
                                 insert_filter("192.168.4.0/24", deny, R3)]}
```

where `network:reach:check1` is the verification rule:

```
policy [subnet4, subnet1]:path {
    assert (action=0)
}
```

We expect that this rule will be executed by the monitor system to verify the network behavior. When this rule is violated, it will emit the following network state {network, path, check1, 0}.

Based on our requirement, when AutoConf receives {network, path, check1, 0}, it has two choices to fix the conflict: running `insert_filter` at router R2 or running `insert_filter`

at router R3. We setup our experiment such that AutoConf selection is biased in the favor of inserting filtering policy at router R3.

In our first run, we injected AutoConf {network, path, check1, 0}. AutoConf invoked first action from the first management cycle. In our experiment the management cycle was 15 seconds. Thus, the average repair time is 7.5 seconds.

We modified the two actions such that the first action modifies the network state by injecting {network, path, check1, 0}, while the second action modifies the network state by injecting {network, path, check1, 1}. This modification is to simulate the case when we add `link1` to the network topology. Inserting filter policy at router R3 will not fix the problem.

We observed the following behavior: In the first and the second management cycle, AutoConf has selected the first action. Then it has adjusted its decision in the favor of the second action in the third management cycle. This implies that the correction has been fixed in 37.5 seconds in average.

Now, we injected {network, path, check1, 0} again. AutoConf fixed the conflict immediately in the next management cycle. The average repair time is 7.5 seconds.

We kept injecting {network, path, check1, 0} at random times. At the 7th injection, the management system has selected the first action, then it has selected the second action. At 7th injection, the average repair time was 22.5.

7.3 Evaluating Verification System using Simulation

In order to thoroughly test our verification framework, we must test it against large–scale networks with varying parameters and sizes. Using only real configuration will limit the number of evaluation scenarios. As such we have developed a tool called `netgen` to generate randomly networks along with valid forwarding control rules. We also modify AutoConf system to accept the tool results. Forwarding access rules are generated as plain text instead of XML files.

We run our evaluation on a computer with Intel Core 2 Duo CPU 2.13GHz and 4GB of RAM. We generated 15 different scenarios with different network sizes. Five scenarios have been configured to generate huge set of complex firewall policies. The remaining scenarios are used to evaluate AutoConf's capability to handle FCL's. The average number of nodes is 600 with 10,000 links. The average total number of FCL rules is 100,000 rules per network.

7.3.1 Topology and FCL Generator

Netgen generates randomly a network topology that consists of three types of nodes: router node, firewall node, and subnet node. Router and subnet nodes are initially placed in a rectangular plane of size $H \times W$ where H and W are matrix height and width, respectively. Matrix height determines the number of levels (hierarchical levels) where nodes in level 1 are always core routers and nodes in level H are always subnet nodes. The distribution of subnet nodes and router nodes in the remaining levels follow a power law probability distribution such that the number of subnets decreases as the level number reaches 1. After placing subnet and router nodes, we interconnect two nodes using the following model:

- The number of links between two levels is controlled by a parameter called branching factor and the number of routers in the upper level.
- Each node at level i is connected to at least one router node at level $i-1$. The selection of router node follows a uniform distribution. If the branching factor for that router has been reached, the next router (to the right) is selected. Please note if the branching factor for all routers at level $i-1$ has been reached, the first selected router will be used.
- There is no link between a subnet node at level i and any node at level $i+1$.
- There is no link between two nodes at the same level, except core routers at level 1. There is a link between two adjacent core routers.

The above model guarantees that we have one connected network topology and the maximum path length is $2 \times (H - 1) + W$.

The next step is to place firewall nodes on links. The number of firewalls is determined by a given percentage. The distribution of firewalls in the graph follows Exponential distribution such that the number of firewall increases as the level number increases.

The routing distribution follows a modified version of RIP protocol. Each lower level router advertises its routing tables to the upper level routers. There is no advertisement from upper level routers to lower level routers. All routers, except the left-most core router, have a default gateway. Firewall rules are generated randomly. However, the address space in each firewall is divided into two sets: internal addresses and external addresses. Internal addresses are the set of all subnet addresses from subnet nodes that are directly or indirectly connected to the firewall node. The remain address space is called external space. Therefore, if a firewall rule consists of source IP address and destination IP address, then one address must be internal and the other address must be external.

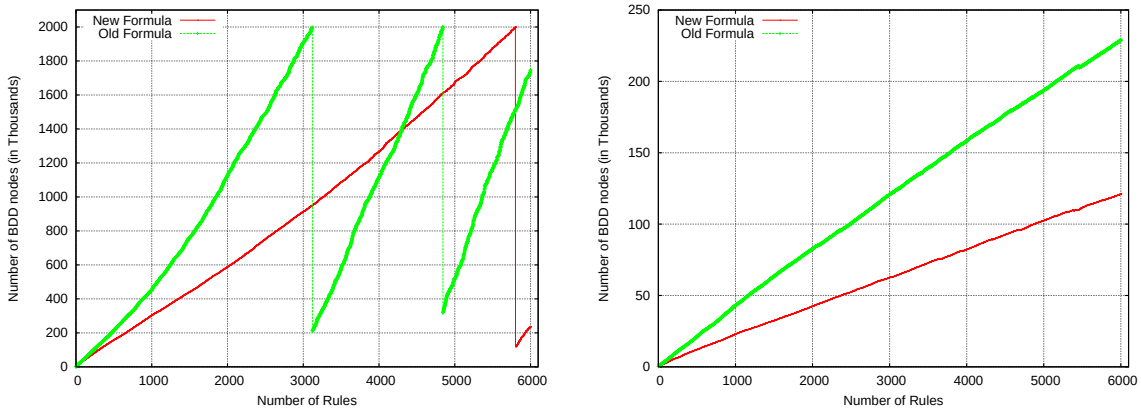
7.3.2 Evaluating BDD Construction

We first show the improved performance of using Equation 4.7 rather than Equation 4.4. Firewall policy is considered the most complex and costly in BDD construction than other policies since it involves all packet header information. Therefore, it is very crucial to evaluate our new algorithm rigorously in terms of memory and time complexities. We configured policy generator to generate random firewall rules as shown in List 8.

Figure 7.5(a) depicts the behavior of old Equation 4.4 and new Equation 4.7 when

```
deny icmp 94.89.242.151 255.255.240.0 18.2.113.185 255.255.255.240
accept udp 18.2.48.196 255.255.255.248 any 159.89.0.0 255.255.0.0 796-1340
accept tcp 64.95.143.128 255.255.252.0 22 18.2.214.214 255.255.128.0 any
accept udp 12.1.24.0 255.255.224.0 21 18.2.130.128 255.255.255.128 1233-6502
deny any 109.102.96.218 255.255.255.254 any 18.2.250.208 255.255.255.240 21
```

List 8: Sample of Firewall rules generated by NetGen



(a) GC is invoked by Buddy (b) GC is invoked explicitly after each rule

Figure 7.5: Comparing between Equation 4.7 and Equation 4.4 in terms of memory complexity

Work	# of rules	Time (in secs)	Our Time (in secs)
FIREMAN [101]	800	2	0.18
ConfigChecker [1]	200,000	1100	116
Quarnet [55]	56,189	126	18

Table 7.2: Time Performance as reported in previous work

constructing a Boolean expression for a firewall policy. We set the maximum number of BDD nodes in Buddy's cache memory to 2 millions nodes. These nodes are used by Buddy when performing BDD operations. It is clearly evident that the old equation (shown as a thick line) is more expensive than the new equation (shown as thin line) because it consumes the cache memory very quickly. Notice that Buddy automatically invokes garbage collection engine to free the cache memory. Figure 7.5(b) shows the space complexity of each equation when the number of rules is less than six thousands. The space complexity of the new equation is almost half of the space complexity of the old equation.

Table 7.2 shows the performance of our new Equation compared to previous work in literature. FIREMAN took less than 3 seconds to construct an ACL with 800 rules as reported in [101]. Quarnet took 2.1 minutes to construct approximately 56 thousands of stateful firewall rules. ConfigChecker constructed 200 thousands rules in approximately 18.3 minutes.

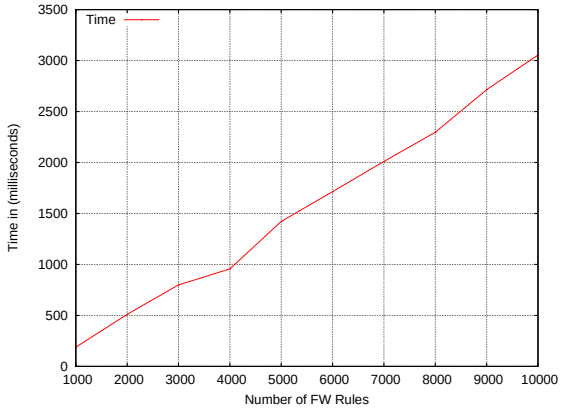


Figure 7.6: BDD construction time for firewall policies less than 10 thousands

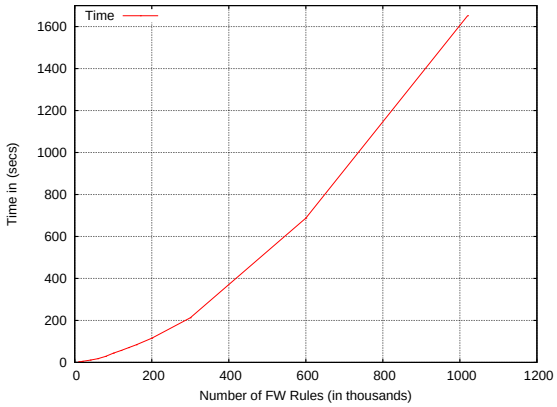


Figure 7.7: BDD construction time for huge set of firewall policies

Figure 7.6 shows that when the number of firewall rules is less than 10 thousands rules, the time complexity of BDD construction increases linearly. With huge set of firewall rules in a network with 480 routers, 720 subnets and 200 firewalls, the graph of time complexity is almost linear as depicted in Figure 7.7. Figure 7.8 shows the space complexity of BDD construction. It is clearly showing that even with very complex firewall policy the memory consumption increases linearly as the number of firewall rules increases.

7.3.3 End–to–End Verification Analysis

In this section we evaluate the performance of AutoConf to analyze network policies in terms of time and space complexities. We generated 15 different networks and divided them into five categories based on the network size. For each category, we computed the average value for each measure. The results of our experiments is shown in Table 7.3.

Category	# of nodes	# of links	BDD time	Alg. 1 time	Alg. 2 time	Update time
1	112	179	2.3s	0.05s	9.6s	0.4s
2	224	305	4.6s	0.08s	19.39s	0.5s
3	392	551	10.16s	0.16s	57.06s	0.98s
4	560	748	14.27s	0.27s	140.76s	2.5s
5	1100	1401	27.32s	0.69s	630.22s	6.1s

Table 7.3: Experimental Results for Analyzing FCL rules

In each test, we run several queries as illustrated in section 4.4 over different network

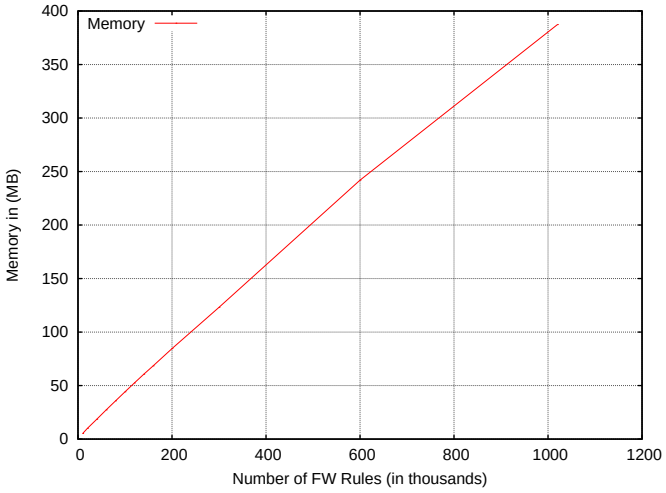


Figure 7.8: Space complexity for BDD construction

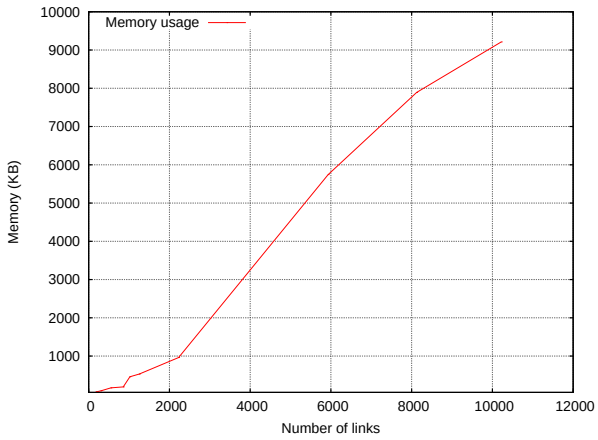


Figure 7.9: AutoConf performance with respect to memory complexity

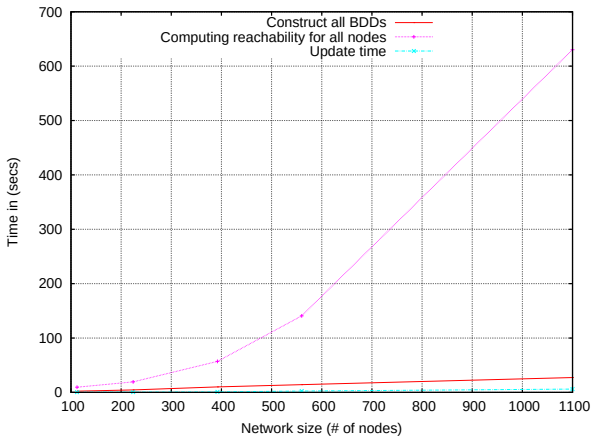


Figure 7.10: AutoConf performance with respect to time complexity

sizes. In all our tests, we found out that the time required to process a query is almost irrelevant to the network size, i.e., between 200 to 350 milliseconds. Moreover, we manually inserted misconfiguration in configuration files and then compared the results before and after inserting misconfiguration. In all our tests, AutoConf successfully detects these misconfigurations.

Figure 7.9 shows the impact of the number of links in a network on the space complexity of the AutoConf system (excluding the space complexity in BDD package). We can see that the space required to build the graph model (including connection predicates) is almost

linear.

Figure 7.10 shows the performance in more details. As shown, the running time to build all connection's BDDs increases linearly while the running time to build all $\mathcal{G}$'s BDDs increases quadratically. As we mentioned the running time to compute reachability for all sink vertices is $O(n^2)$. For a network of size 560 nodes, the overall building time is approximately 155 seconds. Note that AutoConf does not need to compute reachability of all nodes. It computes only the node that is required in verification rules.

To find the running time when updating a node, we manually inserted some new filtering rules for a single device. Intuitively, any update requires the rebuilding of filtering BDD and its connection BDD, and updating its $\mathcal{G}$ expression by invoking Algorithm 3. Figure 7.10 reveals that the running time of update process increases linearly as the number of nodes increases.

7.4 Evaluating AutoConf using Simulation

We developed another tool called RSGen to generates randomly a list of requirements and network states. This enables us to rigorously evaluate our proposed framework for policy adaptation in large–scale networks.

7.4.1 Requirements and State Generator

RSGen conforms to the specifications described in Chapter 5. RSGen does not generates policy rules but rather requirements and metric states.

For generating requirements, inputs to RSGen are number of targets, number of services, number of metrics, number of requirements, average number of goals per requirement, and the distribution of data types.

RSGen starts by generating a table to store the information about each metric specification: metric name, its service name, and its data type. We use uniform distribution to

generate this table. The randomness arises from the relationship between a metric and its service. Based on our specification, it is possible that a single metric belongs to multiple services (like ip-address) or a service has a single metric. Data types are assigned based on the input distribution. Notice that the table size is less than or equal to the number of metrics times the number of services.

Next, RSGen goes into a loop based on the number of requirements. In each iteration, it selects randomly from the metric table above, assigns it to a random target, select a random relational operator, and assigns a random value based on its data types. The metric table will be updated to indicate the regions of valid values.

RSGen generates metric states as follows. It takes as input the percentage of violated states and the metric table. It creates initially a table to keep track the set of metrics used by a given target to avoid any possible conflict. Then, it goes into a loop based on the number of states. In each iteration, it selects randomly a metric from the metric table. Then, it selects randomly a target. If this target has been used before for the same metric, it will select another target. Finally, it generates a random value based on the percentage of violation.

7.4.2 Evaluating BDD Construction

Our plan to evaluate our approach is to study the time complexity when constructing requirement BDD using Equation 5.2 and the time complexity when analyzing the network states to determine the system state based on Equations 5.8, 5.10 and 5.10. Also, we measure the time the management system takes to update system states when a new set of metric states is received.

We start by evaluating the cost of constructing BDD's requirements. There are several factors that affect the construction time: the network size in terms of the number of devices (or targets), the number of services and metrics need to be monitored, and the number of requirements. As such, we divide the metric–spec complexity (i.e., the number of services

Category	Number of Services	Number of metrics
Simple	10	10
Moderate	20	25
Complex	20	50
Very Complex	20	100

Table 7.4: Metric–spec Categories

and the number of metrics) into 4 categories as shown in Table 7.4. For each category, we create different scenarios with different network sizes and number of requirements.

Figure 7.11 shows the time complexity with respect to the number of requirements. Regardless of metric–spec complexity, the time to construct requirements BDD increases linearly as we increase the number of requirements. Also, it reveals that the complexity of metric specification has little impact of the construction time. At 30,000 of requirements, the difference between simple and very complex metric specifications is almost two seconds.

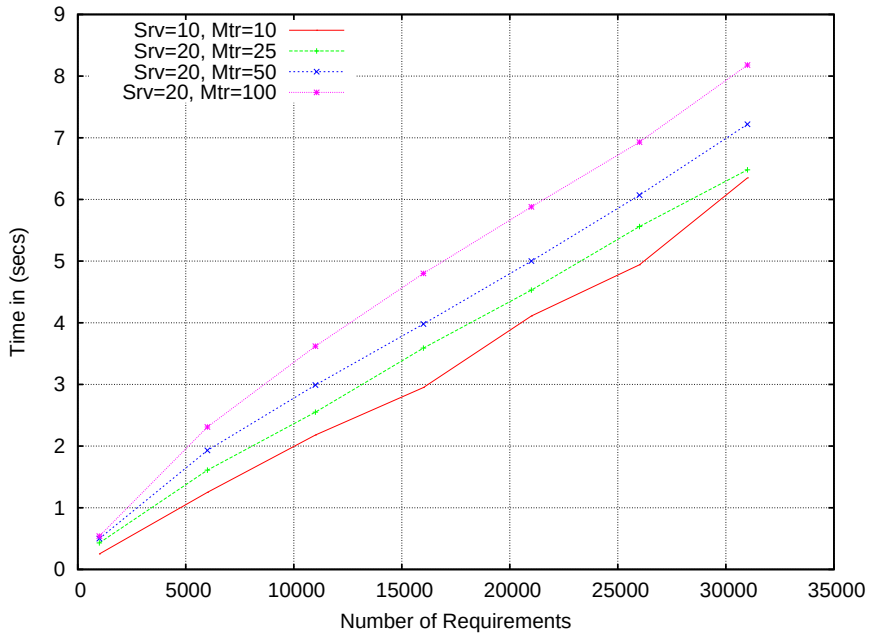


Figure 7.11: The impact of requirement's set size to the BDD construction time

Figure 7.12 shows the impact of network size to BDD construction time for different sets of requirements. In this evaluation, the metric specification is moderate (see Table 7.4). The figure reveals very interesting result. The number of devices has no impact on the

construction time. The reason is that we select an efficient bit ordering for BDD functions (see Section 2.1). This ordering has eliminated the impact of network size on the construction time.

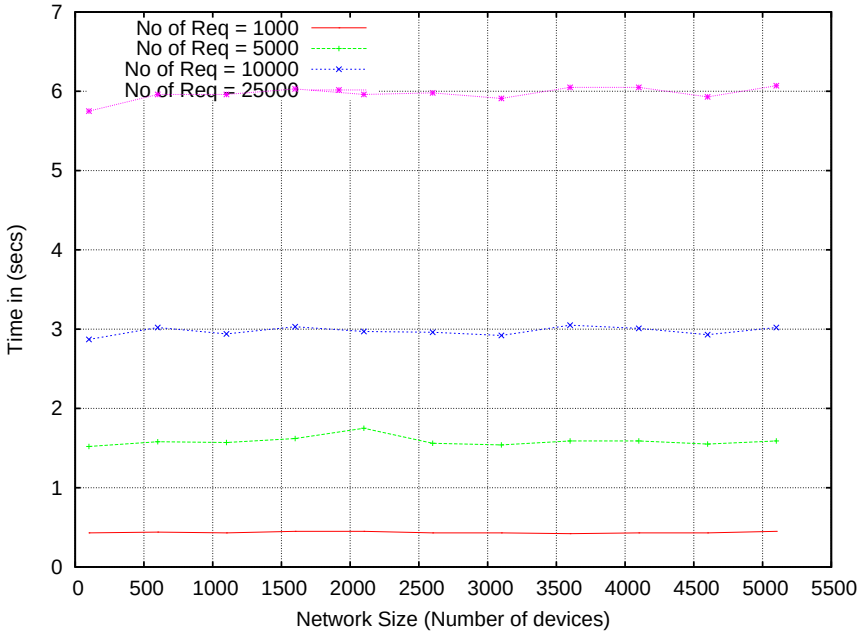


Figure 7.12: The impact of network size to the BDD construction time

The time required to build network state is shown in Figure 7.13. The data is collected for a network of size 1000 devices, number of requirements is 30 thousands, and metric specification is very complex. The result represents the time required to construct system state using Equation 5.6 as well as the time required to analyze a network state using Equations 5.8, 5.9 and 5.10. For 140 thousands metric states, the system requires 15 seconds to obtain the results. Actually, the time required to analyze the network state is almost negligible (less than one second) with respect to the construction time. In all our experiments, the time required to update the system state takes at most two seconds.

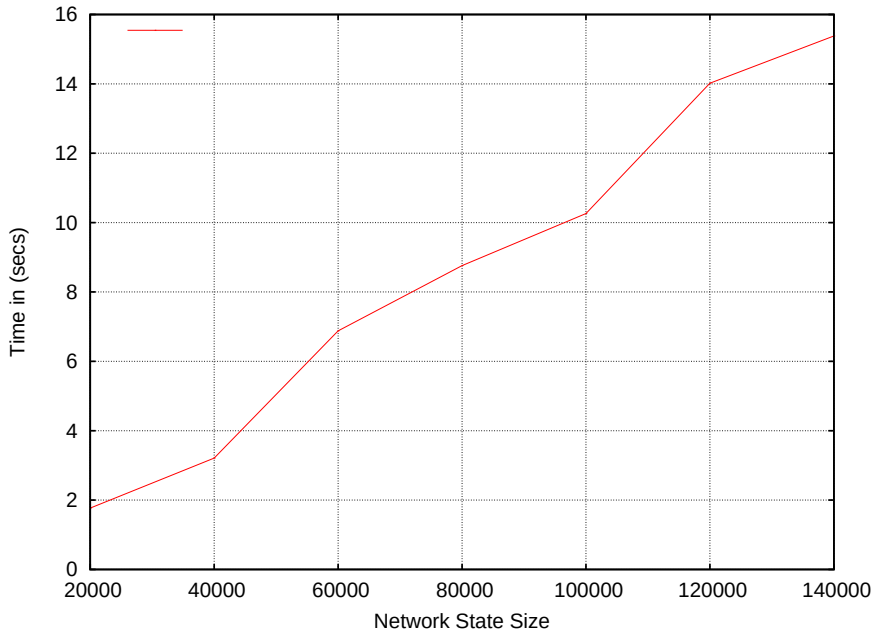


Figure 7.13: The time required to construct network states' BDD

7.5 Summary

We evaluated AutoConf by running several configuration scenarios such as interface configuration, RIP configuration, OSPF configuration and MPLS configuration. To rigorously evaluate AutoConf, we designed and developed several simulation tools to generate various network topologies, high–level requirements and forwarding control lists. Our simulation experiments have shown that AutoConf can process and handle thousands of devices and millions of configuration rules in efficiently and effectively. The response time is all within the acceptable range.

Chapter 8

Conclusion

Managing large networks is extremely complex and error-prone. Automating network configuration is a challenging topic in networking research. Successful network management should not only ensure the correctness of current service configuration but also should guarantee service delivery during the life cycle of managed networks. This dissertation is an attempt to tackle two major problems in network configuration: (1) installation and provisioning of services in a heterogeneous network, and (2) reconfiguration as to maintain reachability, security and performance requirements. We designed a configuration management system called AutoConf not only to automate service configuration but also to adapt its configuration to fulfill high–level requirements. AutoConf consists of three main components: Network Configuration System, Network Verification System and Network Automation System.

We presented in–depth review of the continuous effort of standardized organization to tackle network management and the latest effort of IETF to improve the network configuration management: NETCONF protocol and YANG data model. While NETCONF and YANG provide more effective and simpler configuration management to deal with the proprietary configuration data in heterogeneous networks, there is a limited effort on standardizing common configuration information as in SNMP MIB definitions. Network Configuration System handles this limitation by taking as input Configuration Semantic Model

describing a network and a set of SCL templates for various service configuration that will be translated to generate valid NETCONF-based configuration messages. From these specification, AutoConf generates complete, consistent network configuration on the fly. To truly evaluate the usefulness of the proposed configuration solution, we run AutoConf with different configuration scenarios. We demonstrated how to use CSM abstraction to design and plan the network information. We also demonstrated the interface, RIP, OSPF and MPLS configurations.

General configuration practice is to verify the uploaded configuration and to ensure that the network is operated as intended. We presented a global network verification system that ensures not only the consistency of configuration values that span multiple devices but also the correct behavior for end–to–end reachability and security properties. We introduced a new formalization for modeling routing tables based on prefix length. We also improved the formalization of filtering policies as well as NAT policies. To rigorously evaluate the evaluation system, we designed and developed a topology and configuration generator. We generated different networks that consist cumulatively thousands to millions forwarding control rules. Our experimental results show significant improvement over previous work.

Network Automation System adopts policy–based management for automation and adaptation. Sometimes the network administrator has multiple choices to handle policy conflicts. To enable AutoConf to figure out the best choice, we implemented Dyna-Q algorithm, which is a Q-learning technique that allows the system to learn on–line. We also presented a novel formalization for modeling configuration and expectation policies in order to have a compact representation and to enable us to use Dyna-Q with large–sized networks.

8.1 Limitations

The work presented here is designed to reduce configuration complexity. Our key design philosophy is practicality such that it can immediately be applied to any current network.

However, we still need to overcome the following limitations:

- Not all network devices support NETCONF or YANG architectures. Even though we can resolve it by deploying proxy NETCONF-enabled servers, developing one proxy server can be tedious specially in heterogeneous network infrastructure.

- We assume that YANG modules have different module's prefixes. The purpose of module prefix is to uniquely identify the configuration data within a single module. Since there are no common agreement on management information under NETCONF umbrella, it is possible to have two different modules with the same module prefix. We can resolve this limitation by augmenting module prefix with its namespace. However, namespaces are long and difficult to implement.

- Our adaptive technique learns by trials. It must try all alternative in order to find the best action. Although all alternative actions are based on administration experience, it is possible that one action can put the network in critical state. In the future, this action will not be selected again but it must be tried. We can avoid this from happening by running in a logical network such as ShadowNet [20] to learn the optimal policy.

8.2 Future work

We summarize here some of future areas suggested by our work.

- We designed our management system to adopt other standard management protocols by adding Erlang modules during its running time. However, we did not implement it. Also, it needs to analyze the capabilities of network devices by correlating between device type with vendor-specific MIBs to build up device database. In NETCONF, we achieved this by analyzing the advertised capabilities when exchanging HELLO message.

- In this dissertation, we analyzed filtering, routing and NAT'ing policies. We are planning to extend this analysis by accommodating other policies such as IPSec.

- We designed our system using the Q-learning technique due to its computational attraction and no assumption is required for model convergence. In literature, there are some evidence that function approximation provides better average reward after a long run. The advantage of function approximation is that it does not require memory to store states. So, it is very suitable for learning the behavior of large–scale networks. However, it requires extensive computation and training to optimize function parameters. We are planning to investigate the applicability of using function approximation in network configuration management and measure its effectiveness compared to Q-learning technique.

- The management system we design has text-based interface. We are planning to extend our implementation to support graphical user interface.

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Appendices

Appendix A

YANG language

A data model is basically a conceptual model for configuration information that determines the structure of data, *intra*-relationships between them, and integrity constraints that ensure the correctness of uploaded values during configuration process. Recently, IETF introduced a new standard data modeling language called YANG. YANG is written specifically for network management (domain-specific language). Modern network standards groups such as the Metro Ethernet Forum are adopting YANG as a device configuration standard [87]. In the following paragraphs, we give a brief description of YANG language.

In YANG, management information is partitioned into modules such that each module defines a hierarchy of data which can include complex data types such as lists and unions. The strength of YANG relies not only on its strong support of syntactic and semantic validation rules, but also on its simplicity and easy to read.

List 9 shows an example of a simple YANG module to define some parameters of RIP configuration. The module `router` consists of one hierarchy tree called `rip`. `rip` consists of three nodes: `version`, `network`, and `neighbor`. The node `version` is a simple integer value that can take either 1 or 2 and its default value is 1. The node `network` is a list of records such that each record is a data structure composed of one node: `address`. The keyword `key` is used to uniquely identify the entries in `network` list. The last node in `rip` tree is

`neighbor` node which represents a list of IP addresses.

```
module router {
    namespace "http://cdm.depaul.edu/ns/router";
    prefix router;
    import ietf-inet-types {
        prefix inet;
    }
    /* RIP configuration */
    container rip {
        /* rip version */
        leaf version {
            type int8 {
                range "1..2";
            }
            default 1;
        }
        /* network configuration */
        list network {
            key "address mask";
            leaf address {
                type inet:ipv4-address;
            }
        }
        /* neighbor configuration */
        leaf-list neighbor {
            type inet:ipv4-address;
        }
    }
}
```

List 9: RIP module of YANG

YANG module is very flexible and extensible. For example, the data definition of IP address is described in another module called `ietf-inet-types`. Module `router` extends its data definition by importing `ietf-inet-types` module that contains the definitions of all data types related to TCP/IP protocol suite such as IP address version 4 and 6, port number, domain name, URI, etc. Another important feature of YANG is its direct map with XML schema. For example, a RIP configuration that conforms to List 9 is shown in List 10.

The remaining of this section, we show the YANG modules for interface configuration

(List 11) and OSPF configuration (List 12).

```
<rip>
   <version>1</version>
   <network>
      <address>192.168.1.0</address>
   </network>
   <network>
      <address>192.168.10.0</address>
   </network>
</rip>
```

List 10: RIP configuration in XML

```
module interfaces {
namespace "http://cans.cdm.depaul.edu/linux/interfaces";
    prefix "ifs";
    import ietf-inet-types { prefix inet; }
    import ietf-yang-types { prefix yang; }

    container interfaces {
        list interface {
            key name;
            leaf name { type string; }
            leaf flags {
                type bits {
                    bit LOOPBACK; bit BROADCAST; bit MULTICAST;
                    bit MASTER; bit SLAVE; bit UP; bit LOWER_UP;
                }
            }
            leaf up { type boolean; }
            container link {
                leaf mtu { type uint16; }
                leaf link-type {
                    type enumeration {
                        enum ethernet; enum atm; enum loopback;
                    }
                }
                leaf address {
                    type yang:phys-address;
                }
            }
            list inet {
                key "address";
                leaf address {
                    type inet:ip-prefix;
                }
                leaf broadcast { type inet:ip-address; }
                leaf scope {
                    type enumeration {
                        enum host; enum link; enum global;
                    }
                }
            }
        } // list interface
    } // container interfaces
} // module
```

List 11: Interface module

```
module routing-ospf {
    namespace "http://cans.cdm.depaul.edu/ns/quagga/ospf";
    prefix quag;

    import ietf-inet-types {
        prefix inet;
    }

    revision 2010-06-09 {
        description "first revision.";
    }

    /* OSPF configuration */
    /* Quagga supports only one process */
    container ospf {
        /* configure router ID */
        leaf router-id {
            type inet:ipv4-address;
        }

        /* area configuration */
        list network {
            key "prefix";

            leaf prefix {
                type inet:ipv4-prefix;
            }

            leaf area {
                type union {
                    type inet:ipv4-address;
                    type string {
                        length "1..3";
                    }
                }
                mandatory true;
            }
        }

        leaf-list passive-interface {
            type string;
        }
    }
}
```

List 12: OSPF module

Appendix B

Structured Configuration Language

This appendix gives a description of SCL language.

B.1 Language Primitives

The language is typeless since the data constraints are enforced by Yang not SCL. The basic data type in SCL is called `term` which can be a single value or a complex value. A complex value is either a *tuple* enclosed by {} or a *list* enclosed by [].

SCL expresses the CSM model logically as a set of predicates. Each predicate has the form $\{Q, x_1, x_2, ..., x_n\}$ where Q is the concept name and x_i is an attribute value. For example, the predicate {device, rtr01, 'area-one', [router, abr]} means that `rtr01` is a device that has a parent device `'area-one'` and classified as a Router and Area Border Router(ABR). The existence of single quotation mark in `area-one` is to indicate that `area-one` is a single term; not the arithmetic expression $(area - one)$.

B.2 SCL statements

SCL language has a set of statements. The general syntax of SCL statement is composed of a command name followed by zero or more arguments followed by either a set of subcommands

or a set of values surrounded by curly brackets. When a command has more than one argument, the arguments are separated by a single colon.

B.2.1 Schema statement

A schema is a descriptor that describes the meaning of each term in a tuple. It allows programmers to specify a name for each term in a predicate. As we mentioned before, CSM allows the administrator to define new concepts. This can be achieved by using `schema` statement. The general syntax is

```
schema <ontology_as_concept> {
   <attribute names separated by comma>
}
```

For example, one can define a new schema called `subnets`, which has an IP address, a subnet mask, and attached devices, as follow:

```
schema subnets {
   id, address, mask, attached_device
}
```

B.2.2 Insert statement

Insert statement is used to add new predicates to the database. The syntax is:

```
insert {
   <a list of tuples separated by comma>
}
```

Following our previous example, we can insert new predicates of type `subnets` into the database by typing

```
insert {
   {subnets, 1, '192.168.10.0', 24, [a, b]},
   {subnets, 2, '192.168.20.0', 24, [b, d]},
```

```
   {subnets, 3, '192.168.30.0', 24, [c]}
}
```

B.2.3 Sequence generator statement

Let us assume that a manager would like to assign a unique IP address to a group of machines such that the IP addresses belong to the same subnet. This can be realized by SCL sequence generator statement. SCL enables users to generate two types of sequences: integer sequences and IP address sequences. The syntax of sequence generator statement is

```
sequence <seq-name>:<type> {
   [minvalue <int-value>;]
   [maxvalue <int-value>;]
   [incrementedby <int-value>;]
   [subnet {<net-address>, <int-value>}]
}
```

where `type` can be either `int` or `ip4`. For example, to define a link that belongs to a specific subnet, one can write

```
sequence link1:ip4 {
   subnet {"192.168.1.1", 30};
}
```

Sequence variables are eventually predicates which have the following schema {sequence, name, type, min_value, max_value, inc, value}.

B.2.4 Manage statement

One fundamental statement in SCL is the `manage` statement. This statement, which requires two arguments: device expression and service expression, specifies what service on which device(s) needs to be managed. The following statement says that ALL devices running the service `ospf` in domain `dom1` must satisfy the underlying `config` statement:

```
manage *:ospf (device.parent = dom1) {
   config default {
```

```
    ...
  }
}
```

The next example says that at least *one* device in domain `dom1` running DHCP server must satisfy the underlying configuration:

```
manage 1:dhcpsrv (device.parent = dom1) {
  ...
}
```

List of Symbols and Abbreviations

Abbreviation	Description
ACSE	Associate Control Service Elmenet
API	Application Programming Interface
ASE	Application Service Element
ASN.1	Abstract Syntax Notation One
CIM	Common Information Model
CLI	Command-Line Interface
CMIP	Common Management Information Protocol
CMIS	Common Management Information Service
CMISE	Common Management Information Service Element
CORBA	Common Object Request Broker Architecture
DMTF	Distributed Management Task Force
DOT	Distributed Object Technology
HTTP	HyperText Transfer Protocol
IDL	Interface Definition Language
IETF	Internet Engineering Task Force
ISO	International Standardization Organization
ITU-T	International Telecommunication Union (ITU) - Telecommunication Standardization Sector
JIDM	Joint Inter-Domain Management

Abbreviation	Description
LLA	Logical Layered Architecture
MIB	Management Information Base
MO	Managed Object
NE	Network Element
NEF	Network Element Function block
OO	Object-Oriented
OS	Operations System
OSF	Operations System Function block
OSI	Open System Interconnection
OSIE	OSI Environment
PDU	Protocol Data Unit
QoS	Quality of Service
RDL	Resource Definition Language
ROSE	Remote Operation Service Element
RPC	Remote Procedure Call
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SMAE	System Management Application Entity
SMASE	System Management Service Element
SMI	Structure of Management Information
SNMP	Simple Network Management Protocol
SOAP	Simple Object Access Protocol
SQL	Structured Query Language
TF	Transformation Function block
TMF	TeleManagement Forum
TMN	Telecommunication Management Network
WBEM	Web-Based Enterprise Management

Abbreviation	Description
WS	Workstation
WSF	Workstation Function block
XML	Extensible Markup Language
XSL	Extensible Styesheet Language
XSLT	XSL Transformation