Abstract—In the context of distributed computing various strategies have been developed to share heterogeneous resources across multiple administrative domains. An important challenge that arises in this context is the exchange of information about the provided resources and their dependencies. In the considered field of application of federated Future Internet testbeds, existing work rests upon different interfaces and schematic data models. This aggravates the discovery and management of heterogeneous resources between autonomous facilities. In this thesis an approach is introduced that reutilizes insights of the Semantic Web research to address this issue. As a result, the major contributions are the definition of a description language for federated infrastructures, the design of a reusable architecture for federated resource management, and the implementation of a proof of concept.

Sharing and granting access to geographically dispersed resources is the underlying concept in the field of Distributed Computing[1]. Associated with this, considerable efforts have been spent on architectures to manage heterogeneous resources across multiple administrative domains. We denote this as a resource federation.

A specific field of application is the distribution of experiments between geographically distributed test environments in the context of the Future Internet (FI) research. One method to evaluate new FI approaches is experimental validation. Given the scale, complexity and heterogeneity of the Internet, such an analysis needs to be conducted within large-scale test environments. Therefore, several environments for experimentally driven research[2] have been established mainly within the Future Internet Research and Experimentation[3] (FIRE) and Global Environment for Network Innovations[4] (GENI) initiatives. Since in particular reproducibility and automation is needed to gain scientific knowledge from these experiments, this effort involves all areas of the experiment life-cycle (as depicted in Fig. 1).

This leads to a wide range of interesting research questions and in the last years a variety of frameworks, protocols, and architectures have mainly been designed for the above described purposes. Currently, particular attention is being paid to the Slice-based Federation Architecture[6] (SFA) for resource discovery and provisioning; the cOntrol and Management Framework[7] (OMF) with its Federated Resource Control Protocol[8] (FRCP) for experiment control; the ORBIT Measurement Library[9] (OML) with its OML Measurement Stream Protocol[10] (OMSP) for experiment measurement and resource monitoring. To support the whole experiment life-cycle, it is required to combine each of these approaches, which introduces a number of challenges. This thesis focuses on the two most fundamental ones.

First, for the afore mentioned APIs different, incompatible approaches have been chosen. While SFA is using Transport Layer Security (TLS) enabled XML Remote Procedure Calls (XML-RPCs), FRCP is exchanging signed messages over the eXtensible Messaging and Presence Protocol (XMPP) or Advanced Message Queuing Protocol (AMQP), and OMSP transports data via plain TCP sockets without safety precautions. Therefore, exchanging information between these protocols require significant development efforts.

Second, the interoperability between these approaches is being further aggavated by the usage of incompatible data serializations. Within SFA testbed specific XML-based Resource Specifications (RSpecs) are being used to describe resources within an infrastructure, FRCP is using either XML or JSON depending on the transport protocol, and within OMSP arbitrary tuples can be defined. Based on this, each testbed uses its own independent definitions for resource types, resource control capabilities, resource monitoring information and further management data such as reservation information.

Both issues prevent mutual understanding and minimum interoperation, which has been the major objective of the above mentioned initiatives. In this thesis an approach is introduced that is founded on well-defined semantic information models to address this issue. Based on mechanisms that have their origins in the Semantic Web[10] research, automatic reasoning allows for the required information integration, knowledge inference and abstraction. The objective is to answer two main research questions: (i) First, how to model heterogeneous resource in federated testbeds to support the whole FI experiment life-cycle. (ii) Second, how to design an architecture that supports this approach and is extensible enough to allow further fields of application.

To answer these questions, the major contributions of the present work can be differentiated mainly in three different parts: (i) Semantically labeled, directed multigraphs

1http://ict-fire.eu
2http://geni.net
3http://oml.mytestbed.net/doc/oml/latest/doxygen/omsp.html
have been used to design a canonical information model named Federated Infrastructure Description and Discovery Language[11] (FIDDLE). This includes the definition of federations, infrastructures, abstract resources and services, life-cycle phases, as well as their relationships. (ii) By resting upon a semantic-driven Microservices[12] design pattern, an architecture has been designed called Federated Infrastructure Resource Management Architecture[13] (FIRMA). The design allows to meet the requirements in the given context and its usage in further federated infrastructure contexts. (iii) In order to evaluate these approaches, an extensible, open-source proof of concept framework called FITeagle\(^4\) was developed and used as a reference implementation in several European projects.

In general, the approach forms a basis for further work in the context of distributed resource management such as Intercloud Computing, including federated Software Defined Networking (SDN) and Network Function Virtualization (NFV) islands for flexible network management, big-data analysis, or the Internet of Things (IoT).

\(^4\)http://fiteagle.org

### REFERENCES