Network Virtualization and Resource Description in Software-Defined Wireless Networks

Qianru Zhou, Cheng-Xiang Wang, Stephen McLaughlin, and Xiaotian Zhou

ABSTRACT

Future networks will be defined by software. In contrast to a wired network, the software defined wireless network (SDWN) experiences more challenges due to the fast-changing wireless channel environment. This article focuses on the state-of-the-art of SDWN architecture, including control plane virtualization strategies and semantic ontology for network resource description. In addition, a novel SDWN architecture with resource description function is proposed, along with two ontologies for the resource description of the latest wireless network. Future research directions for SDWN, control strategy design, and resource description are also addressed.

INTRODUCTION

It is widely accepted that future networks will be defined by software. With an ever-increasing demand for broadband communications, new challenges for networks keep coming up, such as intelligent and ubiquitous connectivity, efficient and flexible allocation of resources, etc. To meet these challenges, future networks must support convergence over traditionally separated network domains and offer greater granularity and flexibility in control and in data throughput. With the core idea of separating the control and data planes, software defined networking (SDN) has been considered as one promising approach to meet those challenges in the future.

SDN naturally virtualizes the network architecture and isolates the data/control traffic. The logically centralized control plane, with the global knowledge of the network state, is able to obtain, update, and even predict the global information. Thus, SDN can guide end users to select the best accessing network, or even provide them with services from multiple networks. SDN can be treated as one paradigm, rather than an ossified architecture, where one central software program, the controller, is employed to optimize and dictate the overall network behavior [1].

SDN can naturally be extended to versatile scenarios, such as optical networks, mobile wireless networks, data center networks, and cloud computing. The design of wireless network architecture is much more challenging as it must deal with various physical restrictions caused by the fast-changing nature of wireless channels [2, 3]. In the fifth generation (5G) wireless communications, by implementing SDN in eNodeB, distributing control is proven to have higher efficiency [3]. Server virtualization of wireless networks is also more challenging than that of wired networks, as the former has to satisfy the requirements of both coherency and hardware isolation [1].

Furthermore, to implement multiple control strategies at real networks, a universal agreed description of network resources is needed. However, to the best of the authors' knowledge, no such effort has been reported for software defined wireless networking (SDWN), which will be introduced in Section II. One possible reason might be that the existing test-beds for SDWN are relatively small and simple, thus there is no need to develop specialized technologies for network resource description. Nevertheless, considering the heterogeneous networks that exist in the real world, it is important to reach an agreement on the format and schema to uniquely represent the network resources for all layers. Hence, the massive resources can be possibly manipulated simultaneously with high efficiency.

Semantic Web technologies are believed to be a promising tool for unique resource description. The semantic web is created by the World Wide Web Consortium (W3C), with the intention "to create a universal medium as the exchange of data can be shared and processed by automated tools as well as people" [4]. The goal of the Semantic Web is to define a universally recognized model, which the machines can directly adopt to process and relate the information, as if they can think. With semantic technologies, one can treat the structure of complex hybrid networks as a distributed database, where an SQL-ish language is ready to search, locate, and edit a node or link of the network. Moreover, with a network description language based on a RDF, one can describe the network topolo-

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gy as a flexible and extendable graph to the computer (and also to us).

Semantic technologies have been implemented in optical networks [5]. However, the situation is much more complicated for wireless networks, not only because of the fast-changing channel environment, but also because of the varied service requirements from different customers. Thus, it is a difficult task to describe wireless network resources through semantic technologies. In this article, we focus on this topic and propose an SDWN architecture with the function of resource description, as well as two ontologies for the description of LTE wireless network resources.

The rest of this article is structured as follows. We give an overview of existing SDWN architectures. Current control strategies are introduced and discussed in detail. We demonstrate network description and semantic web technologies. Several current semantic description languages, as well as the software implementations and performance evaluation, are discussed. In this section, we also propose a novel SDWN architecture with resource description module and two ontologies for 5G wireless networks. Finally, conclusions and future challenges are addressed.

SDWN VIRTUALIZATION ARCHITECTURE

SDWN AND OPENFLOW

SDWN, by its nature, is about making decisions on how a connection or a flow is transmitted across the whole network. As mentioned above, the core concept of SDWN is to split the data and control planes. The control plane is responsible for the network resource assignment and decision-making. Once a decision is set, it will communicate with the data plane through a particular protocol to finish the transmission. The most widely adopted protocol is OpenFlow [6]. OpenFlow[1] is the first SDN standard, and hence the most frequently used SDN language. Its inventors deem it as the enabler of SDN. Not only does it configure the network elements, it also provides an open protocol to program the flow-table in different switches and routers. SDWN could solve the problem of network ossification efficiently and make both the control plane and data plane programmable. It also helps new technologies to be integrated and tested in networks considerably simpler, and therefore accelerates network evolution.

ARCHITECTURE DESIGNS OF SDWN

Current SDWN research mainly focuses on network architectures. Existing designs often focus on different positions in the network. For example, RouteFlow [1] focuses on the IP routing services, while FlowVisor [7] and FlowN [8] concentrate on slicing the network physical infrastructure, by placing a slicing layer between the data plane and the control plane. OpenRoads [1] was proposed with the intention to replace current WiFi networks. The details of RouteFlow, FlowVisor and FlowN will now be introduced in this subsection.

RouteFlow consists of two parts, an OpenFlow controller and a RouteFlow server running as an application on top of it. There is a virtual network topology with virtual machines, where the routing engine is installed on each of them [1]. The virtual network topology mirrors the physical network topology. The virtualized topology may not necessarily reflect the exact topology of the real physical infrastructure, due to the nature character of SDN. That is to say, according the state of the real-time communication demand, the controller will mirror the actual physical network in different ways. There are three main mapping schemas: $1:1$, $1:n$, and $m:1$ or $m:n$, where m and n are both positive integers, denoting the numbers of nodes in physical network topology and logical network topology, respectively. These three mapping schemas represent logical split, multiplexing, and aggregation [9].

Another SDWN controller that is built on OpenFlow, called FlowVisor, has already been practically implemented. Since May 2009, it has been deployed into a small network at Stanford University. In this network, FlowVisor acts as a transparent proxy between OpenFlow switches and other OpenFlow controllers, such as NOX [7]. Within FlowVisor, network resources are sliced in various dimensions, by bandwidth, topology or device CPU, etc. It provides much stronger separation between the control and data planes, by slicing the network resources into many orthogonal and independent slices through a transparent slicing layer [7]. It enforces block and rewrite control messages as they pass through FlowVisor [7]. A demo of network slicing in FlowVisor is shown in Fig. 1. Four isolated slices over the same physical network are demonstrated in Fig. 1. In these slices two of them are wireless and two are wired [10].

FlowN inherits similar strategies from FlowVisor, except it adopts a database to help process the mapping between the control plane and physical infrastructure [8]. As a consequence, it takes more time than FlowVisor to process the control message in small virtual networks. However, when more virtual networks are involved, say, more than 100 virtual networks, FlowN turns out to have slightly smaller latency than that of FlowVisor [8]. Note that FlowN with memcached is still slower than FlowVisor. Adopting database technology in virtual network mapping is a promising trend, but a lot of work is still required.

CONTROL STRATEGY

The control strategies could be applied in different layers and different parts of the network architecture. For example, SoftRAN and OpenRAN [1] concentrated on providing software defined centralized control on radio access network; while RouteFlow [1] tries to execute remote centralized IP routing on computer networks. Odin [1] is a SDN framework based on WLAN and can achieve a virtual access point abstraction on physical switches. FlowN [8] is an advanced version of FlowVisor while OpenRoads is a SDWN application based on FlowVisor. Both FlowN and OpenRoads apply software defined control over physical switches [1]. Details

The core concept of SDWN is to split the data and control planes. The control plane is responsible for the network resource assignment and decision-making. Once a decision is set, it will communicate with the data plane through a particular protocol to finish the transmission.

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[1] Although OpenFlow and SDN are often easily confused, they are two totally different concepts [6].

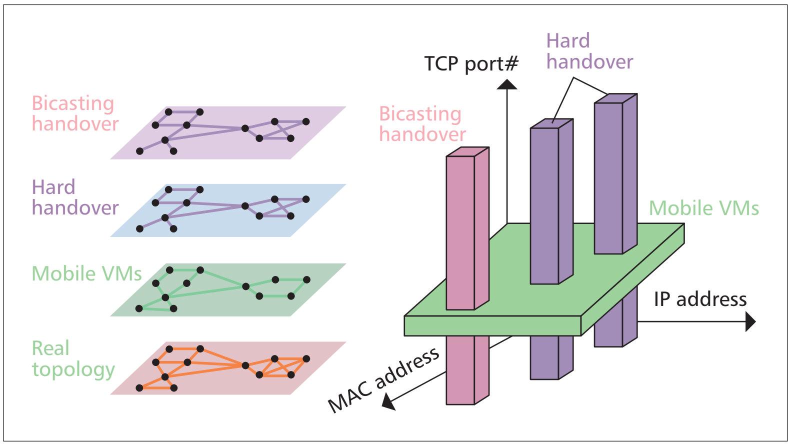

Figure 1. Demonstration of network slicing in FlowVisor [10].

of those control strategies are summarized in Table 1.

Just like FlowVisor, FlowN acts transparently to both control and data planes. Unlike FlowVisor, however, it uses databases to do the mappings between virtual and physical resources. The advantages of FlowN over FlowVisor fall into three categories: Firstly, FlowVisor does not supply a full virtualization over the physical resources as FlowN does. It simply slices them. Secondly, the mapping algorithm FlowVisor adopts is not efficient. For example, it has to iterate every node when doing a mapping. In FlowN, mapping can be done by a simple SQL query. It has been proven to be more scalable in a large network that may contain more than 100 virtual networks [8]. Thirdly, FlowN can supply securer network virtualization. Its physical mapping topology is invisible to tenants, whilst in FlowVisor mapping is exposed to tenants [8].

Network Description Based on RDF

Introduction of Semantic Technology in SDWN

In SDWN architecture design, a fundamental element is the information model, which describes all the resources of the network. This information model is the foundation of network virtualization. It describes both the physical layer infrastructure and its visualization. The ideal information model should be "technology independent, reusable, easily extensible and linkable to other existing models" [11]. Thus, the information models should be built based on an RDF syntax.

In the semantic web all of the information and services can be understood and used both by humans and computers. The semantic web is proposed with the intent of defining a universal model for resource or information description. Rather than trying to teach the machine how to understand human languages, semantic web defines a set of regulations that the machine can use to process the information of resources. The Semantic web is composed of three elements: metadata, RDF, and ontology.

Metadata is the "data about data" [4], which contains the information about the property of data. The RDF is a standard about making statements about the resources. It describes resources in the form of triples. A triple is a form of subject-predicate-object expressions. A set of triples is a graph. More details can be found in [4].

The topology information of a network can be collected and updated in real time from the network. It can be stored in an SQL-like database, in the form of a table with three columns, namely subject column, predicate column, and object column [11].

In semantic web, the ontology is also known as the vocabulary. Although ontologies do not have a universal definition to date, in the field of information science, an ontology defines a set of classes and the links between these classes. More specifically, in network description, the ontology describes a set of nodes and the links between them. It is a body of knowledge describing the network resource domain. The resource domain here is defined by physical entities in networks, such as switches, routers, devices for computation and storage, and the links between them [5].

An ontology describes the network resource with its own layered structure. There are upper level ontology and lower level ontology [15]. The Upper level ontology is the fundamental ontology which can be inherited by all sub-ontologies. It is technology independent, while the lower level ontology is technology specific.

Semantics provide a well-designed structure to describe the information for the resource domains and requirements from the clients. The main goal of network description language is to make sure that all the applications involved in a certain network have the same understanding of the network architecture topology and network resources [11].

Network Semantic Ontology Applications

Until now, the semantic ontology languages proposed to describe the network structure are numberless. These languages have different grammars, different parameters, and different specificities of application. Some of the most well-known ontology proposals are introduced below and their details are given in Table 2. However, a universally accepted language that is able to properly describe the resource of SDWNs has not been proposed yet to the best knowledge of the authors. Two typical ontologies are introduced below.

The Semantic Resource Description Language (SRDL) is the first ontology to describe both network and non-network resources in optical networks. However, the relationship between physical resources and virtualized resources are not provided by this ontology.

Resource Specification (RSpec) is an ontology language provided by GENI to describe SDN resources. In the new GENI v3 schema, RSpec is expanded to describe OpenFlow resources, with the support of FOAM. FOAM is an aggregate manager for OpenFlow resources in the GENI infrastructure.

Due to the complicated and variable wireless channel environment and the emerging new technology, building ontology for wireless networks is a long-term, arduous task. Many

SDWN Applications	Control Strategy	Description
FlowVisor [7]	FlowVisor can apply software control over any physical hardwares, such as routers, switches, by placing a slice layer between the control and data plane. It is already running on a production network in Stanford University.	FlowVisor positioned between an OpenFlow switch and several OpenFlow controllers. FlowVisor can slice any network resources in any control and data plane communication, for example, topology, bandwidth, device, CPU, or forwarding tables.
OpenRoads[1]	A wireless version of OpenFlow testbed, adopting FlowVisor to virtualize the physical WiFi switches, access points, and WiMax base-stations. It is currently running on a small network in Stanford, and is aimed to replace the present WiFi network.	OpenRoads consists of three layers: The flow layer, the slicing layer, and the controller layer. The slicing layer adopts FlowVisor to slice the physical resources. The NOX, an open source OpenFlow controller, is adopted in the controller layer.
FlowN [8]	FlowN is a SQL-based NOX controller, which could provide a full virtualization over a network of physical switches.	With the implement of database, FlowN could map the physical resource to virtual network topology by submitting SQL queries.
SoftRAN [1]	SoftRAN provides an SDN control plane in radio access network, by abstracting the base stations network.	SoftRAN achieves virtualization by abstract the base stations network into a virtual big base station, from which control decisions are sent to all the radio elements.
OpenRAN [1]	OpenRAN provides "match-action" control strategy	The architecture of OpenRAN consists of three parts: wireless spectrum resource pool, cloud computing resource pool, and SDN controller. It provides abstraction on the resources in both data and control plane.

Table 1. SDWN control strategies.

researchers of network semantic ontologies have put the development of wireless ontology on their agenda. Wireless ontology will be the new function of the future version of RSpec.

IMPLEMENTATION FOR SEMANTIC ONTOLOGIES

There are some open-source tools to implement semantic web framework, such as Jena, Sesame [12]. Jena is an open-source semantic framework for JAVA. It supplies an API, which is able to extract data and compose RDF graphs, and an SPARQL engine, which will be introduced below, and a TDB for RDF storage and query [12].

As stated before, with RDF, the network resources can be organized as an SQL relational database with a table of three columns, namely, the subject column, the predicate column and the object column. The resource information can be considered as terms in the database. With ever increasing data being stored in this database, an SQL-like tool is required to search and locate the target information in the ocean of RDF data with higher efficiency. Many SQL-ish query languages have been proposed so far, such as SPARQL, rdfDB, RDQL, and SeRQL. SPARQL is one of the most widely used. It is a powerful query language for RDF, developed and recommended by W3C. Jena supplies a SPARQL engine by an application API — ARQ. It supports operations such as SELECT, CONSTRUCT, DESCRIBE, and ASK queries, etc. [12] Sesame is another powerful JAVA framework for RDF, which is very similar with Jena, except that Jena supports Web Ontology Language (OWL) and Sesame does not [13]. However, Sesame can also supply an easy API for RDF as Jena does. In addition, it can support two query languages, SPARQL and SeRQL, as well as Alibaba, an API that can map Java classes to ontology and generate Java source files from ontologies [13].

PERFORMANCE EVALUATION OF ONTOLOGY

The ontology evaluation is the process to determine which resources the ontology defines correctly/incorrectly and those it does not define. It is a technical judgment for the content of the ontology. Evaluation of an ontology is not only necessary when it is implemented and published, but should be supported during the whole lifecycle of the ontology [14].

The criteria for performance evaluation are consistency, completeness, conciseness, expandability, and sensitiveness [14].

Consistency means every definition in the ontology is consistent and no contradictory conclusion can be deduced from other definitions and axioms. Ontology is consistent if and only if every one of its definitions is consistent.

Completeness is the basic requirement of ontologies, thus, incompleteness is a fundamen-

Semantic Ontologies	Description Technology	Description	Group
Network Description Language (NDL) [11]	Resource Description Framework (RDF)	To describe physical networks	Universiteit van Amsterdam, Netherlands
CineGrid Description Language (CDL) [5]	Web Ontology Language (OWL)	To describe media resources and services in CineGrid exchange	Universiteit van Amsterdam, Netherlands
Semantic Resource Description Language (SRDL) [5]	Web Services Modeling Ontology (WSMO)	To describe IT and network resources of a Service Oriented Optical Internet	University of Essex, UK
Media Application Description Language (MADL) [11]	Resource Description Framework (RDF)	Its purpose is similar with CDL SPARQL is adopted in MADL to supply query on the information models generated.	University of Essex, UK
Common Information Model (CIM) [11]	Unified Modeling Language (UML)	It provides a description of management information for networks of enterprises	DMTF, an industry standards organization
Virtual private execution infrastructure Description Language (VXDL) [11]	XML syntax	VXDL is a language for virtual network resources, it enables users to describe the virtual network topology, including virtual routers and timeline.	Universidade Federal de Santa Maria
Resource Specification (RSpec) [11]	XML syntax	It is a common language for describing resources, resource requests, and reservations. It is currently supported by PlanetLab, ProtoGENI, GENI v3, Omni and Flack, and Orca.	GENI: Global Environment for Network Innovations, a federated testbed. It provides a virtual laboratory for networking and distributed systems research and education.
A Service-Oriented Ontology for Wireless Sensor Networks proposed in [11]	Web Ontology Language Description Language (OWLDL)	It proposes a service-oriented sensor ontology for wireless sensor network environment	Cheju National University, Korea

Table 2. Semantic ontologies for network description.

tal problem in ontologies [14]. Completeness of an ontology is difficult to prove, however, we can prove the incompleteness of the ontology by proving the incompleteness of an individual definition.

Conciseness can be obtained for an ontology if and only if the following requirements are met:

- The ontology does not contain any unnecessary definitions or axioms;
- There are no redundancies between definitions;
- No redundancies can be inferred from other definitions and axioms.

Expandability means that new definitions can be added to ontology in the future without changing the already defined properties.

Sensitiveness is defined by the smallest change in a definition that can affect the already defined properties of the ontology [14].

Broadly speaking, evaluation can be divided into two parts: technical evaluation, which is carried out by developers, and users evaluation. From another perspective, the ontology evaluation approaches contain two aspects: ontology verification and ontology validation [14]. Ontology verification means that the ontology should be built correctly, which means its definition, in the natural language from the real world, matches the ontology requirements and competency questions of the target resource domain precisely. Ontology validation means that the ontology model matches the resource source in the real world correctly. Besides, ontology assessment is to judge the understanding, usability, usefulness, quality and portability of the definitions, taking the stand as the users. Various users and applications need various approaches to assess ontology [14].

The target context for ontology evaluation comprises the following aspects [14]:

- Each individual definition and axiom;
- All the groups of definitions and axioms that are stated explicitly in the ontology;
- Definitions imported from other ontologies;
- Definitions and axioms that can be inferred from other definitions.

In a nutshell, many reports have been published introducing ontology evaluation. However, very few offer details about exactly how the ontologies are evaluated or how the evaluation tools are built for different ontologies.

It is worth mentioning that, just like software testing, ontology evaluation should be performed as early as possible during the developing process of the ontology and should be carried out throughout the entire life circle of this ontology [14].

SDWN ARCHITECTURE WITH RESOURCE DESCRIPTION AND ONTOLOGIES

In this section, we propose a novel SDWN architecture with the resource description module, as well as two ontologies, namely, resource ontology

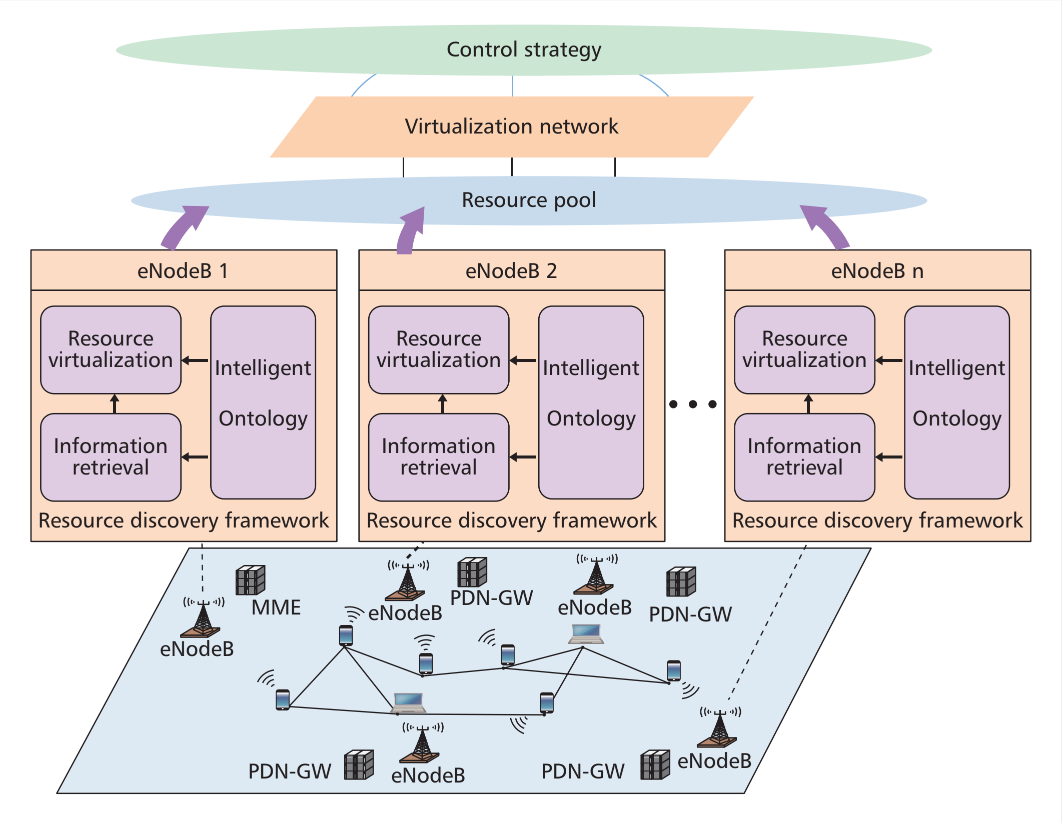

Figure 2. SDWN architecture with resource description function module.

and QoS ontology. Resource ontology is the main ontology for the resource domain in the network, while the QoS ontology describes the requirement for the communication services and the expectation from customers. These are designed for project "Towards Ultimate Convergence of All Networks (TOUCAN)" funded by EPSRC (No. EP/L020009/1). TOUCAN is proposing to develop full network convergence for any elements, domains, devices, and applications. It covers all technical domains, such as the mobile network, WiFi, optical network, and LiFi. In this article, we focus on SDWN. In our design, the control plane is embedded in eNodeB, along with the resource discovery module. This module acts as middleware, where applications can be built upon it.

Such architecture is shown in Fig. 2. The core module is the Resource Discovery Framework, where resource description function is performed. The framework consists of two parts: Information Retrieval and Resource Virtualization. An intelligent ontology translator based on RDF is adopted to syntactically analyze the network resources and customer requests, and translate them into machine-understandable syntax. Using the same ontology throughout the network, the controller can manipulate resources more efficiently.

The proposed resource and QoS ontologies are shown in Fig. 3 and Fig. 4, respectively. Resource ontology in Fig. 3 is the core ontology, which describes the main concepts of SDWN and can be inherited by other sub-ontologies. The number of classes and properties in the resource ontology is limited, because it cannot be technology-specific and it has to be general.

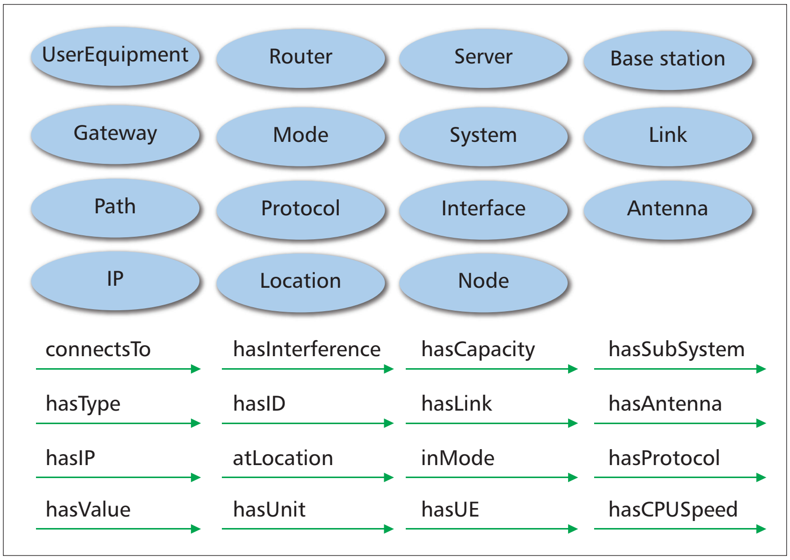

Figure 3. Resource ontology for SDWN.

Consequently, the ontology does not need to be revised every time a new technique or technology emerges. The terms in the ellipse are classes. They are subjects and/or objects, while the terms with underlines are predicates. With this ontology we can express the resources in RDF triples like this: "BaseStation A" "hasAntenna" "Antenna 1," where "BaseStation A" is an instance of class "BaseStation," "Antenna 1" is an instance of class "Antenna," and "hasAtenna" is a property of class "BaseStation."

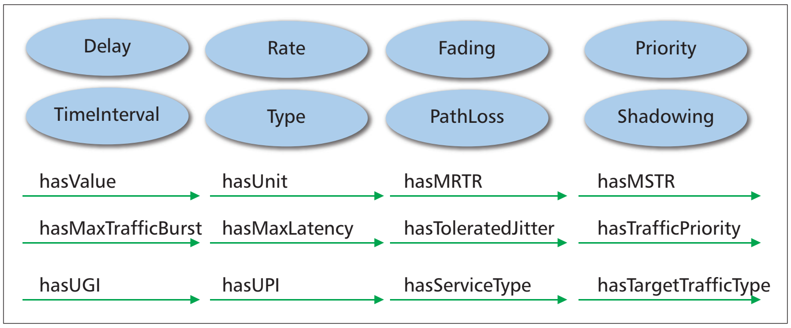

Figure 4. QoS ontology for SDWN.

One of the major goals of network resource description is to precisely depict the network resources and leave the details stay confidential to upper layers. On this ground, we divide the resources into technology-specific and technology-independent resources. Note that only the technology-independent resources are exposed to the upper layers. While resource ontology is technology-independent, the sub-ontologies are technology-specific. The QoS ontology in Fig. 4 is a sub-ontology applied to QoS domain. Just like its variable channel environment, the QoS requirements of SDWN are diverse and flexible. There are audio, video, audio/video streaming, HTTP, online gaming, and social network services, and each one of those has different QoS requirements.

The QoS ontology depicts the key QoS attributes in the IEEE 802.16e standard. The Maximum Sustained Traffic Rate (MSTR) stands for the capping rate level of service flow; Minimum Reserved Traffic Rate (MRTR) means the minimum rate of a service flow; Unsolicited grant interval (UGI) is the time interval between data grant opportunities for an downlink service flow; and Unsolicited polling interval (UPI) is the maximum time interval between polling grant opportunities for an uplink service flow. As stated above, the core ontology can be inherited by sub-ontologies. Thus, we can describe the QoS resources in RDF triples like "Node A" "hasMSTR" "10Mb/s." The subject "Node A" is an instance of class "Node" inherited from resource ontology. Object "10Mb/s" here is a value, rather than an instance of class. In nature language, this triple can be stated as "Node A has a MSTR of 10Mb/s" or "MSTR of Node A is 10Mb/s," but when we describe it in triples, it can be understood by computers.

CONCLUSIONS AND FUTURE RESEARCH CHALLENGES

In this article, we have presented a comprehensive study on a SDWN virtualization strategy and resource description technology. The details of the control strategies, including the network virtualization design and the existing SDWN testbeds architectures are presented. The key technology to implement network resource description, semantic web technology, has been introduced in detail along with its three key elements including metadata, ontology, and RDF. We also have presented the performance evaluation methodology for SDWN at current stage. We have proposed a novel SDWN architecture adopting the semantic technology for the resource description. The ontologies for wireless network, including resource ontology and QoS ontology, have also been reported.

The ontologies proposed in this article are just sketches. We will continue to refine the ontologies by evaluating them on real-life applications. Eventually we will evaluate these ontologies using our own wireless testbed. Technical issues about how to extract resources from current network management system also need to be addressed.

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