Making Software-defined Networks Semantic

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Abstract: This position paper identifies the increasing role of the controller in radios and radio networks. The paper defines wireless software-defined networks. A new cognitive radio ontology is proposed that is a hierarchical abstract description of the communication/networking scenario, RF devices, policies, and tasks. Radio protocols can also be described in a similar way. The ontology provides awareness and supports reasoning by the controller and applies to any RF device. Directions for future work are also briefly discussed.

1 INTRODUCTION

There are currently several important trends in wireless radios and networks. We believe that all of these trends appear as a result of the increasing role of the controller. Every radio has a controller, which is responsible for providing and managing the sets of user interfaces that are necessary to set up and take down communications sessions. Some of the first people to think about the expanding role of the controller were in the Software-Defined Radio (SDR) community. In a SDR, the controller has to support a new set of functions that are associated with changing radio protocols. The original concept of the controller assumed that a particular fixed radio protocol was to be "switched in," therefore the controller was referred to as a "switcher".

Cognitive radio has emerged as a concept in the last ten years. The ITU defines cognitive radio as a radio that can "obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained" (ITU, 2009). Some cognitive radios address only dynamic spectrum access and are implemented at layer 2, without a change in the legacy MAC. These are narrowly-defined cognitive radios. A cognitive radio must have domain knowledge of radio communication. Based on this knowledge, the cognitive engine (CE) can "dynamically and autonomously" optimize the various parameters and protocols.

Recently, the area of Software-Defined Networks (SDNs) has emerged (Bahl et al, 2006; M. Mendonca et al, 2013). SDN are based on the idea of decoupling of network control from the forwading plane, i.e. SDN take the increasing role of the controller to the networking level. SDN enable network virtualization, which allows the physical network to be viewed as an abstract pool of resources. The SDN controller can handle the configuration of network components taking into account various policies and applications. The main motivation for SDNs so far has been flow-based routing, where flows from different sources are routed differently. This requires the forwarding hardware module to be programmable via an open interface.

It is of considerable interest to extend the SDN concept to radio networks. Somewhat following ITU's terminology, we define wireless SDN as "networks, where all protocols can be set or altered by software, excluding changes which occur during the normal pre-installed and predetermined operation of a network according to a system specification or standard". We recognize that SDNs require in general all protocols to become software-defined, including physical layer, MAC, etc. It can said that a SDN is a system-of-systems, where previously independent components form a new system with new capabilities. Cognitive radio networking (CRN) is an example of a new capability. These CRNs can acquire knowledge about the network and dynamically and autonomously adjust their parameters taking into account this knowledge, pre-defined objectives, and previous experience. For example, CRNs can respond to interference, device density, and end-user application requirements.

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Current wireless networks are far from this vision. Currently, heterogeneous wireless networks are not software-defined; once configured, it is not possible to incorporate a new and different RF device without new hardware and/or new software being installed. Current networks lack abilities to self-configure. Self-configuration is desirable at the device and at the networking level.

After the initial self-configuration, the RF device shall have sufficient capability to communicate with other devices and can obtain additional configuration parameters. The next step after self-configuration is self-optimization, where the network and its RF devices can automatically take actions based on the available information, prior knowledge, policies, and objectives that have been specified. For example, when a node drops off the network, traffic is re-routed around the missing node as necessary to complete the transmission path. In general, it is desirable to adjust the parameters of the MAC sublayer of the data link layer and the physical layer, and all protocols to achieve a certain objective. One objective can be to minimize interference. Yet another objective may be to configure a radio as a relay and in this way extend the coverage area of a network.

At present, all radios contain an internal repository of useful information that is accessible using Simple Network Management Protocol (SNMP) through the radio's internal IP address for devices that are connected to it. This repository is the radio's Management Information Base (MIB). The MIB typically contains information that describes the frequency, bandwidth, quality of service, interference or collisions with nearby networks, and so on. This information is heavily dependent on the physical layer and the MAC layer of the data link layer of the given wireless systems. The information available through the radio's MIB cannot be understood by other wireless systems. For example, in a network of heterogeneous RF devices there will be multiple MIBs and it is impossible for one RF device to interpret the MIB values of a different device. The presence of MIBs do not make devices and *networks* software-defined.

Cognitive radio networks require considerable interaction among the RF devices and the applications that run on them. The different RF devices must communicate to the network their observations and operational states. This information is much richer than common link status information. For example, one radio might send a list of all emitters it has recently sensed to other devices in the network. The entry for each emitter might include a frequency range, time, spatial location, and signal format (e.g., spread spectrum or narrow-band FM). This requires an appropriate abstraction, or language. The network also must communicate its changing operational settings with all wireless devices.

It is recognized that one of the main bottlenecks in achieving this vision is the lack of an appropriate language (Kokar et al, 2008; Cooklev and Cummings, 2008). This language has variously been called a meta-language, a policy language, a functional description language, and a network description language, among others (Kokar et al, 2008; Cooklev and Cummings, 2008). This language must allow different types of radios and networks to autonomously negotiate with each other to specify and configure themselves in an optimal fashion given their capabilities, environment, and the objectives of their users.

A cognitive radio ontology has been developed by the SDR Forum (Wireless Innovation Forum, 2010). However, this ontology cannot describe the topology of a radio. It also tries to define fundamental wireless communication parameters such as "bit", "symbol", "chipping sequence", etc., which is at an inappropriate level of abstraction for describing SDNs. The ontology of the SDR Forum is mostly used for adaptive modulation to minimize the size of the bit error rate (BER). We believe this functionality is best left to the physical layer. As a result, this ontology is at the same time not sufficient and adds too much overhead. Furthermore, parameters such as "symbol" have different meaning for different radio protocols. For example, for multicarrier modulation systems "symbol" has a different meaning than for single-carrier systems. One approach is to extend the cognitive radio ontology by providing all possible symbol definitions. However, it is more important to address first the question what are the parameters that should be described by a RF ontology. This question has not been adequately addressed by the ontology 1.0. We propose a cognitive radio ontology 2.0 that takes a holistic approach. The operational benefits of our ontology include seamless interoperability of heterogeneous RF devices, reduced interference, and abstraction of device interfaces, which facilitates assigning tasks to legacy radio devices.

2 ONTOLOGIES

An ontology is a data model that represents a domain, in our case a wireless networking environment, and is used to reason about the individuals in the domain and the relations between them, thus providing a way to represent knowledge in a standard way. Note that the unified modelling language (UML), a language for specifying software systems, and ontologies converge.

The Resource Description Framework (RDF) is a simple ontology language that describes things using triplets, e.g., subject, predicate, and object (Cooklev and Cummings, 2008).

An ontology language, such as the Web Ontology Language (OWL), can be used to described a RF Device (moving or stationary), a radio transmission policy, and a task, such as spectrum sensing, frequency jamming, and so on. An ontology, once represented in OWL, defines vocabularies for representing meaning of a subset of domain-dependent terms and the relationships between these terms. Using an ontology, information can be annotated, shared, and reasoned over across heterogeneous domains, applications, and platforms. Specifically, the ontology can be used to describe classes, properties, individuals, and data values. The language allows us to define relationships between classes, such as containment. It also allows us to identify individuals that belong to classes and set their data and object properties. While the domain of a data property is a primitive type, such as integer or string, the domain of an object property is an object. Note that it is possible for an object to have zero or more values for a given property and these values do not need to be of the same type.

3 SEMANTIC RADIO NETWORKS

We propose a hierarchical description, describing the communication/networking scenario, RF devices, policies, and tasks with the following main parameters.

3.1 Communications/Networking Scenario

- Setting/terrain
- RF environment
- Interference
- Mobility
- RF device types
- Information type
- Security
- Network topology/NetworkProfile/NeighborList
- QoS parameters

3.2 RF Device

- Time-Of-Day
- Remaining Battery Level / Power spent while inactive (but powered on)
- Location
- RF front-end parameters
- Digital hardware parameters

3.3 Policies

- regulatory policy
- service provider policy
- user policy
- mission policy
- security policy
- vendor policy, etc.
- spectrum usage policy (spectrum etiquette)

3.4 Tasks

- transmit
- receive
- spectrum sensing

With this abstraction the developed ontology can describe any signal impinging on the receiver's antenna and leverages the VITA 49 standard (Cooklev and Nishihara, 2013).

Transmitting and receiving can be considered as tasks. The waveform to use (e.g., GSM or WiFi) is a parameter of a task. The duration of the task, the start time, and the frequency range are all other tasks parameters are recorded in the ontology. The task to function as a relay can be considered as an ordered sequence of the transmit and receive tasks. The topology of wireless networks changes dynamically. Therefore, it is important to enable self-configuration. When the topology of the network changes, some radios may be given the task to begin functioning as relays.

An important practical consideration is latency. In general, it can be assumed that the latency is on the order of tens of milliseconds. Parameters that change more often are left out of the description.

The ontology provides knowledge, i.e. it makes the logically centralized controller in a SDN aware of all parameters. The next step is reasoning based on the ontology. A reasoning problem is deciding if an OWL description is consistent and deciding if one description is subsumed by another. An OWL reasoner can help us determine if the description contains any contradicting information. Similarly, an OWL reasoner can help us determine which capabilities of a SDR conflict with existing over-the-air policies.

Modern radio protocols are very complex, but are not optimal in all scenarios. A physical layer can be optimized to operate over long range, or high mobility, or power efficiency, or some combination of these parameters, to work in different environments like urban, rural, and so on. Moreover, the use of different antenna types (such as directional antennas) may affect the operation of the radio protocols. Typically, standards groups translate scenario requirements into technical standards that work well on average. Fixed physical layers have options that turn on and off certain features. The developed ontology takes this process further and enables all protocols to become software-defined.

Service providers can advertise in a service registry the descriptions of their capabilities. Every service has a service profile – what inputs does it require and what outputs does it provide, and a service model – how does it work. The ontology must provide declarative APIs for the automatic execution of the services. Clients can search using an ontology query language, interpret these descriptions, and select appropriate services. This enables dynamic discovery of services. Automatic service discovery is the automatic discovery of devices that provide particular services, without prior negotiations between clients and service providers. Queries can be made and answered using appropriate unicast or broadcast messages. Information messages can be sent automatically without requests. Their transmission may be periodical or triggered by certain events.

Heterogeneous nodes can use the ontology to discover networks and networking opportunities (for peer-to-peer communication) for user data transmissions. Without a coexistence mechanism the nodes searching for networks or networking opportunities would use technology specific network search mechanisms, such as scanning the whole band separately with each technology that the node is capable and willing to use for user data communication.

Note that not all devices in the network are software-defined and/or cognitive (using dynamic spectrum access). The ontology enables the logically centralized network controller to be made aware of legacy devices that cannot communicate using ontology descriptions. In this way the network controller can have a global view of the network, taking into account all RF devices.

4 CONSIDERATIONS FOR CELLULAR NETWORKS

The ontology in the previous Section is general, applying to any physical hardware component or system that interfaces with the RF spectrum. In special cases such as cellular and WLAN, a number of parameters are known and therefore do not need to be described. Cellular networks at present have significant challenges such as dense deployment, limited spectrum, consumer demands for data rate, interworking with WLAN, etc. To address these challenges current cellular networks, before establishing a certain capability, employ many protocol exchanges between a mobile device and different components of the cellular network such as base station, radio network control, access gateway, etc. At best, it is unclear that these exchanges are optimal. We propose a methodology according to which cellular networks can better address the challenges that they are facing. For example, public land mobile networks (PLMNs) can be provided with a control plane using such abstract descriptions. Further investigation of the controller structure and protocol exchanges is an appropriate topic for further research.

5 CONCLUSIONS

In this paper we survey the evolution roadmap of wireless radios and networks. The increasing role of the controller is identified as the main theme for this evolution. We advance a comprehensive ontology for SDN. The ontology describes the network, the RF devices, their components and protocols that they support, the policies, and the tasks to be performed. Note that services are moving from human-to-human and machine-to-human to machine-to-machine interactions. Services are available at the "enterprise level". A given service, such as voice, can involve many heterogeneous devices.

The operational benefits of the proposed technology include:

- Seamless introduction of new RF devices,
- Reduced interference
- Exact description of the RF signal impinging on the antenna in order to provide complete RF situational awareness
- Abstraction of device interfaces, which facilitates assigning tasks to devices.

The implementation benefits of the proposed ontology include modularity and common interfaces.

Note that these ontology descriptions may reuse some of the higher layer functionality – for instance, using TCP to communicate to a peer process. We do not consider this a layer violation since the layering of functionality only applies to data packets. We assume that these ontology descriptions are sent over a logical control channel. It can be mapped to a physical channel in a variety of ways; however this is not discussed in the paper. It must be noted that in dynamic spectrum access schemes certain ontology parameters (such as spectrum occupancy information) must be delivered before they become outdated. This problem is related to the way the logical control channel is mapped to a physical channel and is not addressed in the paper. We consider the overhead introduced by the ontology to be small and negligible compared with high data-rate wireless protocols such as IEEE 802.11n, LTE-Advanced, etc.

Several topics are identified for further research. The hierarchical approach can be continued to make the radio protocols software-defined. Typically, standards groups translate scenario requirements into technical standards. We allow in principle this process to be done automatically. In other words, now there is a collection of resources (for example, modulation and coding schemes) from which a physical layer can be designed. The benefits of the proposed solution are simpler and faster integration of products from multiple sources and lower cost of upgrades. This has been investigated recently for important special cases such as local area networks and wide-area networks (Tinnirello et al, 2012; Gallo et al, 2013; De Mil et al, 2014; De Poorter, 2008). Other problems for future work are the automatic generation of the ontology and reasoning with inconsistent ontologies.

REFERENCES

Report ITU-R SM.2152, 2009. Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS).

Mendonca, M., Astuto, B., Nunesy, A., Obraczka, K., Turletti, T., 2013. Software Defined Networking for Heterogeneous Networks, *IEEE MMTC E-Letters 8, 3 36-39*.

Bahl, P., Chandra, R., Padhye, J., Ravindranath, L., Singh, M., Wolman, A., Zill, B., 2006. Enhancing the security of corporate Wi-Fi networks using DAIR. In *Proceedings of the 4th international conference on Mobile systems, applications and services, MobiSys '06,* ACM.

Kokar, K., Hillman, D., Li, S., Fette, B., Marshall, P., Cummings, M., Martin T., Strassner, J., 2008. Towards a Unified Policy Language for Future Communication Networks: A Process. In *DySPAN'08*, Chicago, IL.

Cooklev, T., Cummings, M., 2008. Networking Description Language for Ubiquitous Cognitive Networking. In *Software Defined Radio Technical Conference*, Washington, DC, USA.

OWL 2 Web Ontology Language Profiles (Second Edition) http://www.w3.org/TR/owl2-profiles/

Cooklev, T., Nishihara, A., 2013. An Open RF-Digital Interface for Software-Defined Radios. *IEEE Micro*.

Wireless Innovation Forum, 2010. Description of the Cognitive Radio Ontology, WINN-10-S-007.

Tinnirello, I.; Bianchi, G.; Gallo, P.; Garlisi, D.; Giuliano, F.; Gringoli, F., 2012. Wireless MAC processors: Programming MAC protocols on commodity Hardware," In *Proceedings IEEE INFOCOM,* pp.1269-1277.

Gallo, P.; Garlisi, D.; Giuliano, F.; Gringoli, F.; Tinnirello, I.; Bianchi, G., 2013. Wireless MAC Processor Networking: A Control Architecture for Expressing and Implementing High-Level Adaptation Policies in WLANs. *IEEE Vehicular Technology Magazine,* vol.8, no.4, pp.81-89.

De Mil, P., Jooris, B., Tytgat, L., Hoebeke, J., Moerman, I., Demeester, P., 2014. snapMac: A generic MAC/PHY architecture enabling flexible MAC design. *Ad Hoc Networks*, vol. 17, pp 37-59.

De Poorter, E., Latré, B., Moerman, I., Demeester, P., 2008. Symbiotic Networks: Towards a New Level of Cooperation Between Wireless Networks. *Wireless Personal Communications,* vol. 45, issue 8, pp 479-495.