5-2014

A Comprehensive and Hierarchical Ontology for Wireless Systems

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***Abstract*—This paper presents a comprehensive radio ontology. The ontology describes the communication/networking scenario, the RF devices, their components and protocols that they support, the policies, and the tasks to be performed. The developed ontology enables wireless Software-Defined Networks (SDN) composed of abstract heterogeneous Radio Frequency (RF) devices.**

***Index Terms*— ontology, cognitive radio, reconfigurability, software-defined networking, protocols**

I. Introduction

DRIVEN by the seemingly insatiable market demand for wireless services, radios and radio networks continue to experience rapid evolution. This rapid evolution is making the wireless infrastructure dense, heterogeneous, and overall rather chaotic. Radio resource management (RRM) decisions (i.e., deciding what spectrum to use, at what power, etc.) made at one device, such as a base station (BS) or access point (AP), have substantial impact on neighboring networks and vice versa. Similar problems exists in infrastructure-less military networks, where the term “spectral fratricide” is used. Configuring networks manually is expensive and not optimal. The way forward appears more and more clearly to be autonomous processes.

In this paper, we propose a fundamentally new approach of wireless networking. We argue that all radio frequency (RF) devices should be abstracted as elements of a virtual wireless network. Instead of naively assuming that every RF device is performing independent RRM decisions, we propose that all RF devices are performing coordinated RRM decisions, where resources, such as space, time, and frequency, are software defined and programmable by a logically centralized controller. We recognize that performing coordinated RRM decisions within a *homogeneous* wireless network is not a novel idea. Here we advance the state of the art by proposing coordinated decisions in a *heterogeneous* network. The key to accomplish this is a comprehensive wireless ontology that describes all relevant parameters, such as networks, devices, and policies. The ontology allows the RF devices to update the global view at the control plane and also allow the control plane to communicate back to the RF devices. Note that in this paper we abstract the concept of “RF device”.

In Section II, we review related technologies. Section III gives a quick overview of ontologies. The proposed ontology is described in Section IV. The use of the ontology for reasoning is discussed in Section V, followed by a concluding discussion in Section VI.

II. Background

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 communication sessions. Some of the first people to think about the expanding role of the controller were in the Software-Defined Radio (SDR) community. SDR as a concept has been known for about 20 years. The International Telecommunication Union (ITU) defines SDR as a radio “that allows the RF operating parameters including, but not limited to, frequency range, modulation type, or output power to be set or altered by software, excluding changes to operating parameters which occur during the normal pre-installed and predetermined operation of a radio according to a system specification or standard” [1].

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”. In a SDR, the radio protocols at the baseband level are implemented on programmable platforms such as general-purpose processors, digital signal processors, or field-programmable gate arrays (FPGAs), which increases the cost and power consumption of SDRs.

Cognitive radio has emerged as a concept in the last ten years. In a narrow sense, cognitive radios are devices that can obtain knowledge of the spectrum occupancy and adjust the RF spectrum that they occupy accordingly. The XG specification is a relevant development [7]. XG addresses only dynamic spectrum access and is implemented at layer 2. It does not require a change in the legacy MAC as the legacy MAC need not be aware of XG. Such narrowly-defined cognitive radios require some programmability in the RF front-end. However, they do not have to be implemented using FPGAs and therefore are viewed by some as low-cost alternatives to SDRs. 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” [1]. Therefore, 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. Therefore, dynamic spectrum access alone is insufficient, in general, cognitive radios require fully programmable (and therefore SDR) platforms.

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 [4-6]. This language has variously been called a meta-language, a policy language, a functional description language, and a network description language, among others [4-6]. 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 [17]. However, this ontology cannot describe the topology of a radio. It also tries to define fundamental wireless communication parameters such as "bit", "symbol", and so on, which is at the wrong level of abstraction for describing SDNs. Furthermore, without proper justification the cognitive radio ontology assumes a direct-sequence spread-spectrum physical layer and tries to define "chipping sequence". 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. Note that 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 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 [17].

We propose a cognitive radio ontology 2.0 that does not start with the ontology that is developed within the SDR Forum. 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.

III. 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.

The Resource Description Framework (RDF) is a simple ontology language that describes things using triplets, e.g., subject, predicate, and object [5].

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.

We use the OWL 2 direct semantics as our ontology language, which is the de facto standard for the semantic web [8-14]. Note that OWL 2 ontologies are primarily exchanged as RDF documents. We use Protégé [10] to create the ontology. The ontology is created using the Manchester Syntax for OWL [9], which provides user-friendly compact syntax for OWL 2 that is closer to natural language than RDF. Our example scenarios use embedded Java code that uses the OWL API interface [11] to connect to the reasoning engine. We use the HermiT software [12] to perform the ontology reasoning. It is well integrated with Protégé and it passes the OWL 2 conformance tests for direct semantic reasoners.

IV. Wireless Ontology

We propose a hierarchical description. The main description follows a hierarchical structure, describing (1) The communication/networking scenario, (2) RF devices, (3) policies, (4) tasks, and (5) radio protocols. The parameters are discussed succinctly next.

Communication/networking scenario parameters

- *Setting/terrain*
- *RF environment*
- *Interference*
- *mobility*
- *RF device types*

Describes the types RF devices that are available and their main characteristics (stationary, mobile, etc.)

- *Information type – video, voice, data*
- *Security*
- *Network topology/NetworkProfile/NeighborList*
- *QoS parameters*:
    - *Service Type*
    - *Average/Minimum Throughput*
    - *PacketSize*
    - *Delay/Jitter*
    - *Outage probability*
    - *Blocking probability*
    - *Congestion Probability*
    - *ConnectionAttempts (per hour)*
    - *Average Number of Ongoing Calls*

RF device description

- *Time-Of-Day*
- *Remaining Battery Level / Power spent while inactive (but powered on)*
- *Location*

RF front-end

- *Antenna* (Several parameters)
- *Reference Point Identifier*
- *Bandwidth*
- *IF/RF Reference Frequency*
- *Gain*
- *Receiver sensitivity (dBm)*
- *Radio reception threshold (dBm)*
- *ReceiverNoiseFigure*
- *Reconfiguration Time / Tune Time / Switching Time*

Reconfiguration Time is the time to reconfigure the RF front-end. *Tune Time* is the time that it takes for the receiver to tune to from one frequency band to the next. Typically the tune time will vary depending on which frequency band the system must tune. *Switching Time* is the time it takes for the system to switch from Tx-to-Rx or vice versa.

- *Device Type*
- *Receive Instantaneous Bandwidth*
- *Receiver Dynamic Range*
- ADC / DAC parameters *(Number of Bits)*
- *Bandwidth (bits/second)*
- *Timestamp / Timestamp Adjustment*
- *Timestamp and Frequency Accuracy and Calibration parameters*
- *Transmitter Dynamic Range*
- *Power*

With this abstraction the developed ontology can describe any signal impinging on the receiver's antenna. The description of the RF front-end leverages the VITA 49 standard [15-16]. VITA 49 is a packet-based protocol to convey digitized signal data and metadata (or context data) pertaining to different reference points within an RF frontend.

Digital hardware parameters

- *ProcessorType* (ARM, x86, …)
- *SupportedReconfigurationMethod* (Partial, Full)
- *ReconfigurationTime*
- *MemoryDepth*

Software parameters

- *FFT sizes and processing times*
- *Supported/Installed/Active Waveforms and Protocols*

Policies

- *regulatory policy*
- *service provider policy*
- *user policy*
- *mission policy*
- *security policy*
- *vendor policy, etc.*
- *spectrum usage policy (spectrum etiquette)*
    - *Allowed Frequency Bands for Transmission*
    - *Emissions mask for allowed frequency bands*
    - *Emissions mask outside operating bands*
    - *Emissions during power on initialization*
    - *Emissions during reconfiguration (such as band change, etc.)*
    - *Maximum Transmit Time*
    - *Presence of a physical control channel (rendezvous beacon)*
    - *Antenna Radiation Pattern*

Tasks

Transmit

- *Waveform*
- *Number of frequency intervals*
- *Frequency Range 1 Start / Frequency Range 1 Stop*
- *Power*

- *TimeDuration / StartTime*

Receive

- *Waveform*
- *Number of frequency intervals*
- *Frequency Range 1 Start / Frequency Range 1 Stop*
- *TimeDuration / StartTime*

Spectrum Sensing

- *Number of frequency intervals to scan*
- *Frequency Range 1 Start / Stop*
- *SensingFrequencyResolution*
- *TotalSensingDuration*
- *Detection Type / Detection Value*
- *Scan Dwell Time Per Band*
- *SensingStartTime / TimeDuration*
- *QuietPeriods*
- *SensingLocation*
- *Number of averages*
- *RequiredReliability / ReportingRate / ReportingMode*
- *Noise Power*
- *Signal Level*
- *Traffic Pattern*
- *Identified signal type*
- *Censoring Scheme*
- *Sensing algorithm to use*

RADIO PROTOCOLS

- *Source coding*
- *channel coding*
- *channel access method*
- *modulation*

Messages can be sent in response to requests or automatically, even without requests. In general, these parameters are time-varying; some parameters (e.g. interference) change on the order of milliseconds, some (e.g. battery life left) change on the order of minutes, and some (e.g. mission policy) perhaps less often. Parameters that change very fast (e.g. radio channel coefficients) are not specified and best left to physical layers to handle.

V. Reasoning

The ontology provides knowledge, i.e. it makes the logically centralized controller in a SDN aware of all of these 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. For example, the description of a wireless transceiver can be extensive and contain hundreds of statements. 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.

For example, a rule in our ontology is that we can expect longer delay spread if the network is outdoors and/or there is no line of site between the RF devices. In turn, this can be used to adjust some parameters of the physical layer or to use new algorithms.

The ontology also provides information about the mobility of the RF devices. Some devices may be stationary (base stations and access points), and some are mobile or portable such as phones and computers. Stationary devices usually belong to wired networks. The mobility of devices will impact the protocols. It is known that for devices that are highly mobile certain physical layers and protocols are preferred. For example, OFDMA, SC-FDMA, hybrid ARQ (HARQ), and IEEE 802.16e, are techniques appropriate for mobile devices. Furthermore, OFDMA is known to be more appropriate for downlink, and SC-FDMA – for uplink. The type of data that is transmitted is a key factor. Different protocols may be used for video, voice, and data. The ability to reconfigure the networking protocols based on the type of data is known to be one of the main drivers for SDNs.

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.

Our ontology also describes different policies for transmission. One more policies can be assigned to every RF device. An OWL reasoning engine can determine if a RF device is following the policies that are assigned to it. Policies can be regulatory, service provider, user, mission, security, and vendor specific. A spectrum usage policy restricts the transmission of an RF device. This can include the allowed bands and the amount and type of emissions that are allowed. The way data is transmitted and the existence of a physical control channel can also be part of a policy. Another parameter that we record in the ontology is the radiation pattern of the antenna. For example, the ontology has a rule that antennas with omnidirectional pattern should be used for mobile RF devices.

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.

VI. Concluding discussion

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 that enables wireless SDN, characterized by much higher performance than current networks. The developed ontology has a hierarchical structure and is an abstraction. 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 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 outside of the scope of 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.

The ontology enables radio protocols to become 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.

While the developed ontology is comprehensive, we recognize that there cannot be one set of parameters acceptable to the entire RF community. Our description method allows new parameters to be easily introduced. Applications that are established on top of the ontology can ignore parameters that they do not understand. The ontology allows sophisticated reasoning algorithms, which lead to cognitive radio networks. This is a topic for future research.

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