Representation of spectrum sensing experimentation functionality for federated management and control

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***Abstract*—Spectrum sensing is one of the core functionalities of a true cognitive radio (CR) that supports operation over a broad range of frequencies and can autonomously adapt transmission parameters to the operating environment. There are several types of hardware ranging from sophisticated (i.e. Nutaq Radio420X FPGA mezzanine card) to low cost (i.e. WiSpy) that can be used to experiment with spectrum sensing. This hardware is available for use in several testbeds across the world (i.e. ORBIT, w-iLab.t, TWIST and LOG-a-TEC). Each testbed provides a specific mechanism to define, deploy and execute experiments making it difficult for an individual researcher to use more than one testbed. In this work we propose an information model for describing spectrum sensing functionality with the ultimate goal of developing and promoting a Common CR language that can describe the resources in existing GENI and FIRE testbeds.**

I. Introduction

The need for a common vocabulary to represent various aspects of a radio transceiver has been recognised a while ago in Mitola's seminal work [1] with further steps in this direction being taken by several works such as [2], [3]. Furthermore, in order to boost innovation in the networking domain and support smaller players, the existing testbeds created under several global initiatives (FIRE in Europe, GENI in US, Akari in Japan) are working towards open, general purpose, and sustainable large-scale shared experimental facilities in the form of open multi-user experimental testbeds. The aim is to lower the entry barrier towards experimentation in realistic environments that has been previously limited to highly trained professionals. One way of achieving this is to provide powerful software tools and physical large scale testbeds to benchmark, tune, and optimize applications and services. As discussed in [4], "*the common ground for the converging technologies is formal representation and publishing of semantics such that computers are capable of processing them and reasoning about them.*" In order to achieve this, the community driven Testbed as a Service Ontology Repository (TaaSOR) that provides an abstraction layer over heterogeneous testbeds is used.

Our ultimate goal is the development of a complete ontological description of radio communication in general and wireless networking in particular which is a very complex task. This task could be considered infeasible keeping in mind that semantic descriptions are context dependent. The closer to a general common truth one is, the more complex it becomes to correctly describe specifics of the domain knowledge. Because of these complexities, we focused our attention on the development of a basic vocabulary for spectrum sensing as the foundation for a more general semantic CR language.

While existing efforts such as IEEE 1900.6 [2], the IETF PAWS [3] and CREW CDF [5] define parameters and data structures that are appropriate for spectrum sensing, it is not possible to perform machine reasoning on top of them. In this paper, we build on existing wireless information representation terminology from [2] and [5] and develop an abstract information model that enables us to define and reason over specific aspects of a cognitive radio experiments. This information model is materialised as an ontology represented using the Web Ontology Language (OWL) [6] that is then plugged into TaaSOR alongside other existing domain specific networking ontologies such as NOVI [7] and NDL [8]. We also define a number of use cases that are specific for cognitive radios and validate our ontology on devices from the CREW federation[1] and ORBIT testbed [2]. To the best of our knowledge, this is the first effort to represent and reason over spectrum sensing knowledge as well as the real validation of such a system.

The contributions of this paper are: 1) the identification of representative radio and spectrum sensing related use cases, 2) the development of an ontological model that abstracts device capabilities and enables device and testbed independent representation and querying and 3) an implementation and validation on existing devices under a federated platform.

Section II of the paper discusses specific spectrum and radio related use cases and Section III then introduces relevant abstractions. Section IV implements the abstractions using semantic web technologies and validates the implementation on the TaaSOR system while Section V summarises the paper.

II. System-level Use Cases

Figure 1 presents the way wireless testbed federation can be achieved using the Testbed-as-a-Service with Ontology Repository (TaaSOR) approach [4]. It describes how semantic descriptions are used to scale a set of testbeds into a federation supporting a large community of users. Note that several ontologies are used, each with a specific purpose. Therefore, a scalable collaborative ontology repository is used to provide dynamic access to different sets of ontological resources on demand. Each of the federated testbeds is assumed to have a device inventory where RDBMS or XML descriptions of the devices in the testbed are available. This inventory can then be lifted

[1]Cognitive radio experimentation world (crew), http://crew-project.eu

[2]Open-access research testbed for next-generation wireless networks, https://www.orbit-lab.org/

by means of the dedicated service in the TaaSOR (step 1 in the figure) which then does a semi-automatic mapping (step 2) between the database resources and the semantic resources. Additional descriptions can also be achieved by extracting information from external resources such as html pages using testbed specific ontologies (step 3). Rules can then be inserted into the system (step 4) specifying various facts about the devices and their capabilities. All these steps lead to a knowledge base that can then be queried by users through web services (step 5).

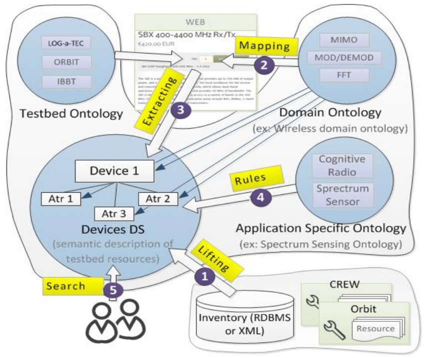


Fig. 1. Wireless testbed federation with TaaSOR.

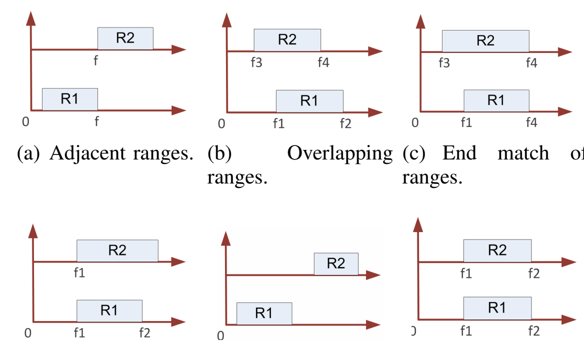
From an experimenter point of view, the capabilities of devices can be described at several different levels, one of them being from the lowest to the highest level of data granularity: I/Q samples, sweep, power spectral density (PSD), RSSI, spectrogram and other. The analysis with respect to the output provided by the device, required settings, and required device capability is provided in Table I.

It is not always possible to get the lower level data, and it is not always trivial to transpose data between the types. The calculation of PSD values already results in information loss, so it is not possible to recover I/Q samples from them. While I/Q samples provide the whole information about a signal, they have to be processed to get the power of the signal. This processing usually changes depending on the situation, for example spectral resolution can be varied with the same input data. Additionally, in some cognitive radio sensing algorithms, it is enough to know the overall energy in a given spectrum band. On the other hand, for other algorithms it is necessary to extract more advanced features of a signal (cyclostationary feature detector). This would not be possible with a device that is only capable of outputting RSSI values.

It can be seen from the Settings column in Table I that, depending on the device capability, desired data granularity and output, terms such as bandwidth, sweep duration, frequency, etc, should be searchable. Thus, in the case of experiment description for cognitive radio, a basic requirement is to be able to query the operational capabilities of devices. More specifically, the frequency values supported by the baseband processing, the intermediate frequency and the radio frequency that is generated at the antenna should be represented and queried in a device independent manner. This is necessary because any experimenter will look for these capabilities in order to select the target testbed for experiments. Figure 2 presents possible situations that may occur with respect to frequency related aspects. For instance, Figure 2(a) represents a situation where two frequency bands (or ranges) are adjacent. This situation can occur in queries where the same device or two different devices are able to perform a task in adjacent frequency bands. We should note here the very nature of the concept of frequency, that is defined in a continuous space, and is similar to how the concept of time is defined. This analogy allowed us to model some of our frequency related definitions on corresponding concepts in the time domain [9].

Other requirements refer to representing the devices using information such as name, description, supported software such as drivers, firmware, operating system and application and their location and capabilities in terms of mobility. For instance, an experimenter may want to run the same experiment on a set of very expensive and very capable devices and on very low cost and limited capability devices to quantify the difference in performance for their algorithm. Such query can be implemented using pure frequency range representations and/or using device name and capabilities. Furthermore, often specific drivers and other software is needed to support the implementation of the experiment, thus the need to also support device specific queries for such situations.

Finally, other testbed specific aspects such as interference levels, geographic placement (i.e. urban, suburban), indoor/outdoor, etc, might also be interesting for the experimenter and the existing ontology can be extended to cover them as well.



(a) Adjacent ranges. (b) Overlapping ranges. (c) End match of ranges.

(d) Start match of ranges. (e) Range lower. (f) Range equals.

Fig. 2. Range specific use cases that should be captured by the representation.

III. ABSTRACTIONS

In order to provide an abstraction over spectrum sensing experiment configuration across heterogeneous devices, we developed an ontology having three orthogonal parts allowing the description of (i) spectrum related theoretical aspects similar to the ones presented in Figure 2, (ii) device spectrum sensing capabilities and (iii) ranges of values.

a) Spectrum related theoretical aspects: are hard to capture in a clear information model represented as an ontology because they require harmonizing the terminology used by domain experts. For instance, when doing a spectrum sweep we can say that we sweep a portion of a spectrum, a range of frequencies, a frequency band or a frequency channel depending on the context we are working in. Representing this in an ontologically consistent manner will most likely bring along the disagreement of some domain experts. In the PAWS draft standard information model there is a *DeviceCapabilities* entity which may be described by a list (array) or *FrequencyRanges* where each *FrequencyRange* is described by a *startHz* and *stopHz* frequency value. In our approach, a *RadioDevice operatesIn* a *FrequencyBand* which is a *subClassOf FrequencyRange*. The *FrequencyRange*, and therefore also the *FrequencyBand*, has *startsAt* and *endsAt* property that connect it to a *StartFrequency* and *EndFrequency* respectively which are then both *subClassOf RadioFrequency*.

TABLE I. ANALYSIS OF DEVICE CAPABILITY STARTING FOR DATA GRANULARITY.

Data granularity	Output	Settings	Meaning	Device
I/Q samples	A set of samples that can reproduce full information about the spectrum with the given and defined bandwidth	Sampling rate (BaseBand-FrequencyBand), center frequency.	Gives full information about captured signal. The result is dependent on the post-processing.	Requires software defined or custom built device to get this type of the data. High data rates as I/Q samples need to be processed fast.
Power Spectral Density (PSD)	One measurement sample	Radio bandwidth, integration time.	Expected power that a signal has in the selected passband.	Spectrum analyzers, software defined or custom build radio devices.
Sweep	A sequence of measurements in different frequencies	Radio bandwidth, frequency bin, sweep duration	A sequence of individual Power Spectral Density measurements.	This is the standard way how spectrum analyzers provide data.
Received Signal Strength Indicator (RSSI)	One sample, or set of samples when in sweep mode.	Bandwidth, center frequency	Many devices can report RSSI values, the danger is the actual data representation. There no clear definition of RSSI provided.There are couple of definitions, some even not referring to dBm.	Usually provided as high level metric in of-the-shelf wireless network cards.
Spectrogram	Time-frequency matrix of sweep, RSSI or PSD values	Time/Frequency data	We can use either RSSI, sweep or any type of FFT data	
Channel statistics	Anything else that can tell something about the occupancy of the band (channel).		Channel statistics are created out of other technology dependent metrics, like achievable modulation rates.	Of-the-shelf network interfaces provide technology specific metrics that can help in creation of channel statistics.

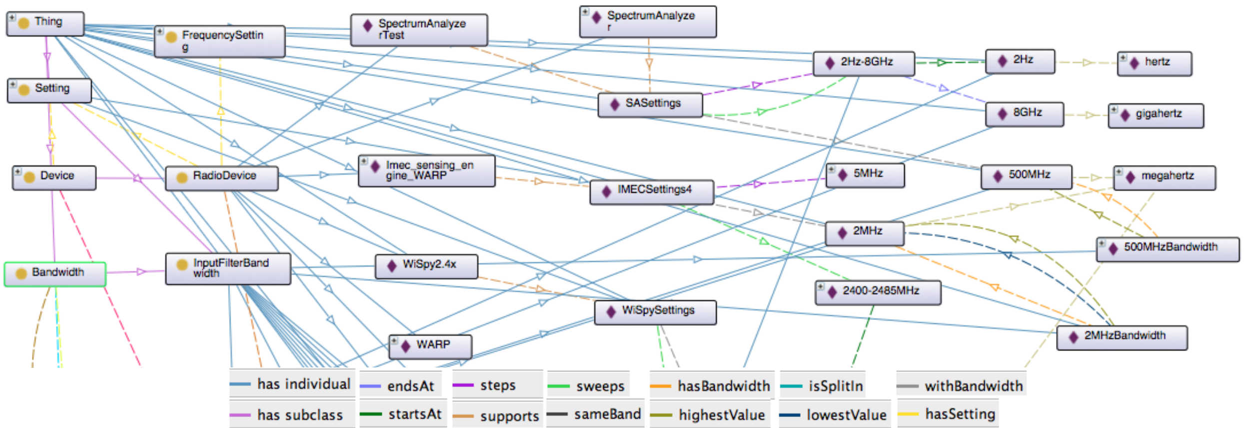


Fig. 3. Snapshot of the knowledge base describing the spectrum analyser.

TABLE II. EXAMPLE DEVICES AND CONFIGURATIONS.

Device	Scan range	Scan bandwidth
Spectrum Analyzer	2Hz - 8GHz continuous interval	0-500 MHz continuous interval
WiSpy	2.4 - 2.495 MHz continuous interval	58.036 - 812.5 kHz continuous interval
IMEC-WARP	2.400-2.485 MHz with steps of 5 MHz	2 MHz
VESNA (TI CC1101)	470 - 862 MHz	1700 KHz

b) Device sensing capabilities: depend on a wide range of devices such as spectrum analyzer versus WiSpy. It can be seen from Table II that a spectrum analyzer can scan any frequency anywhere between 2Hz and 8GHz with a continuously tunable input filter bandwidth of up to 500MHz while the IMEC-WARP has a limited number of possible settings, one example being scanning the frequency band 2.400-2.485 MHz with steps of 5 MHz and an input filter bandwidth of exactly 2MHz. The most reasonable way of representing this, given the (i) large variety of devices and capabilities and (ii) the technology and practices available in the semantic web, was to assume that everything is a continuous interval (or range) as discussed in the examples from Figure 2.

TABLE III. CAPABILITY REPRESENTATION USING THE ONTOLOGY.

0-500 MHz	**2MHz**
500MHzBandwidth isa InputFilterBandwidth	20MHzBandwidth isa InputFilterBandwidth
500MHzBandwidth hasBandwidth 500MHz	20MHzBandwidth hasBandwidth 20MHz
500MHzBandwidth lowestValue **1Hz**	20MHzBandwidth lowestValue **20MHz**
500MHzBandwidth highestValue 500MHz	20MHzBandwidth highestValue 20MHz

With this approach, the representation of the spectrum analyzer's input filter bandwidth and the IMEC-WARP's input filter are represented in Table III using the ontological concepts shown in Figure 3. The *lowestValue* and *highestValue* object properties help distinguish between continuous intervals and individual values. This requires generating a large but finite number of individuals describing frequencies, bandwidths and bands. Alternative approaches would be to (i) model intervals and values independently and (ii) only model single values and use an exhaustive list of these. With the first approach, the model would become very complicated and the abstract reasoning would be based on extremely long and complicated rules. With the second approach, the possible values for devices such as spectrum analyzer would be considerably larger than with our approach (i.e. an interval is not finite).

c) Ranges of values: For representing the actual values and ranges, we used already existing abstraction from OM ontology [10] containing concepts related to physical phenomena and units of measurement.

IV. IMPLEMENTATION AND VALIDATION

We defined the ontology[3] and example individuals representing a subset of spectrum sensing devices available in 4 heterogeneous testbeds. A snapshot of the portion of the resulting knowledge base (=ontology+instances) is presented in Figure 3. It can be seen that a *SpectrumAnalyzer* belongs (*isa*) to the class of *RadioDevices* and it is represented by the

[3]The ontology and individuals are available at https://github.com/cfortuna/CROntology.

SpectrumAnalyzerTest instance. It supports of set of settings represented by the *SASettings*. It is able to sweep the 2Hz-8GHz *AntennaFrequencyBand* which starts at the instance represented by 2Hz and ends at the one represented by 8GHz. The 2Hz *RadioFrequency* instance has a numeric value of 2 and is measured in Hz.

An example query realizing the functionality from Figure 2(f) is presented on the left side of Figure 4. The query is implemented in SPARQL and looks for devices that can sweep bands that start at the same value of frequency and end at the same value of frequency. These SPARQL queries as well as any other user defined queries can be tested with the online version provided by the TaaSOR instance[4]. It should be noted that device capabilities (in this case operating frequency ranges) were lifted by automatic procedure from individual testbed descriptions (services) and the operating frequency ranges are defined with different units (kHz, MHz and GHz).

The complex query on the left hand side of the figure can be reduced by keeping only the first 6 lines (step 1) and defining a rule called *sameBand* (step 2) and using it in the resulting query (step 3). This is equivalent to implementing a function in a typical programming language. While SPARQL queries look like more complicated SQL, it may worth noting that, the testbed user will not be faced with implementing them. Rather, they will be used as an underlying layer of a web based user interface, similar to for instance an airplane ticket booking web service. In this case, the query found that the frequency band (620 MHz) is supported by USRP devices in iMinds and ORBIT ("RF SBX band" and ,"RF WBX band"), VESNA spectrum sensing platform deployed at Jozef Stefan Institute ("470-862 MHz") and the spectrum analyzer that is available at Technische Universität Berlin ("2Hz-8GHz").

V. Summary

This paper focused on the development of a vocabulary for spectrum sensing as the foundation for a more general semantic radio language. First, it identified representative radio and spectrum sensing related use cases that are fundamental to any repository storing and indexing cognitive radio devices. Second, it developed an ontological model that abstracts device capabilities and enables device and testbed independent representation and querying. The model was created according to ontological best practices, uses the Web Ontology Language and is easy to extend or plug into more generic ontologies as a domain specific component. Finally, it provided and implementation and validation on existing devices by plugging it to the Testbed as a Service Ontology Repository. The result is an abstraction layer over heterogeneous testbeds that enables testbed-independent queries for the identified use-cases.

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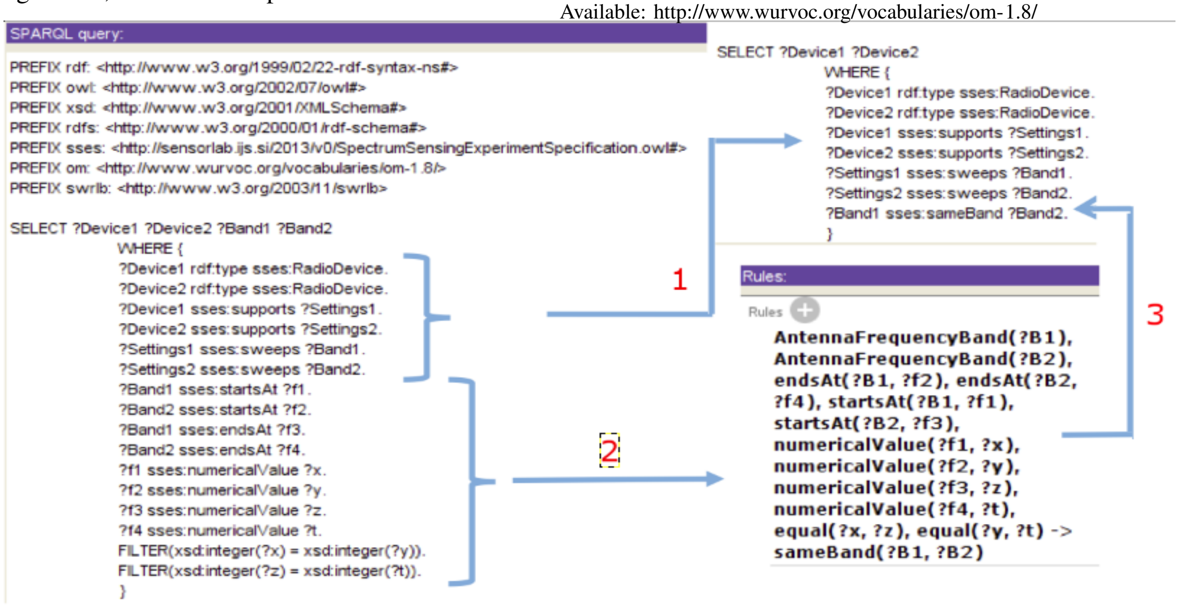

Fig. 4. Example SPARQL query for the range equals situation as presented in Figure 2(f).

[4]see for example SPARQL query named ListContainingBands at http://www.orbit-lab.org:8080/TaaSOR/?project=TaaSORProjects:OrbitInventory