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Design of knowledge models and algorithms for identifying, collecting and storing information

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Abstract:

This document addresses the aspects of knowledge models as well as the processes for identifying, collecting and storing information that can lead to knowledge. It provides a set of explanations and presents the meaning and the type of knowledge that can be built with respect to scopes such as user profile, device profile, network capabilities and policies. Moreover, it relates to previous work in the scope of WP11 in terms of information such as User, Context and Policy information acquisition and argues upon the possible formats and structures of the stored data. The document also proposes a set of knowledge models that relate and capture various aspects of the cognitive radio system. The elaborated work gives a basis for the forthcoming research work related to the scope of WP11 in terms of learning mechanisms, exploitation of derived knowledge and knowledge sharing.

Keywords: Knowledge Management, Information acquisition and storage, knowledge models.

Document Revision History

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0.2	30.12.2011	UKIM	Updated Table of Contents
0.3	24.04.2012	RWTH	Contribution from RWTH is added
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0.5	10.05.2012	UPRC	Initial contribution from UPRC added
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1.0	30.07.2012	UPRC	Finalization of the document

Executive summary

This document provides a set of knowledge models related to various aspects of cognitive radio systems and the processes that relate to the identification, collection and storing of information that can lead to knowledge.

First, the document addresses the aspects of identification of information useful for the process of building knowledge. Section 2 elaborates on the various information types (e.g., user information, device/terminal information, context and network information, etc.) that can be used for the knowledge building process. Moreover, the section introduces the aspects of a system's decision behaviour as a valuable set of information that provides the possibility for knowledge building in terms of self-management and self-awareness of the system.

Section 3 focuses on the aspects of information acquisition and storage. Section 3.1 relates to the work elaborated upon in D11.1 in terms of the information acquisition aspects giving a brief overview of the User and Context information as well as the Policy acquisition processes. Section 3.2 discusses the aspects of information storage in terms of the formats and structures of the stored data and its relation to the collected information that reflect the behaviour of the given network. It introduces the aspect of Radio Environmental Maps as a possible means of data modelling and information storage and relates this to user information, transmitter information, propagation information, Radio Access Technology (RAT)/operator information, and spectrum usage information, among others.

Section 4 proposes a set of knowledge models that capture various aspects of the cognitive radio system such as user/device modelling, environment modelling, and network device status modelling, among others. Section 4.1 elaborates on the aspect of knowledge management in relation to cognitive radio systems, bridging the gap between the work elaborated in Section 3 and the work elaborated in Section 4. Section 4.2 introduces aspects of ontology based knowledge modelling. The work presented focuses on high-level service harmonization, which is not usually discussed in the cognitive networks domain. In relation to cognitive wireless networking the described work indicates that ontology enabled knowledge bases and knowledge models are one of the candidate approaches for both establishing common vocabulary as well as enabling reasoning based on description logic. Section 4.3 explores the relations between spatial and graph based models of wireless networks as possible knowledge models for cognitive radio systems arguing that for a number of application scenarios it is of interest to develop knowledge models in a step-wise fashion. These knowledge models can be used for knowledge representation and storage and for different applications at the run-time of the network. The remaining part of Section 4 focuses on the user profile, device profile and policy knowledge models for cognitive radio systems, elaborating on their format and parameters in use.

Finally, Section 5 concludes the document highlighting its importance within WP11.

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1. Introduction

Learning capabilities, i.e., learning mechanisms, represent an essential feature of cognitive radio systems that enable self-organization and management of the system and increase the reliability of the cognitive decision making process. They also provide the possibility for proactive handling of challenging issues that can decrease the performance of the cognitive radio system; they do this by identifying such issues and mitigating their impact on the system even before they occur.

One of the goals of the learning processes in cognitive radio systems is the building of knowledge by introducing the concept of *Knowledge Management*. Knowledge Management can be defined as a strategy, framework or system designed to enable the acquisition, analysis, application and reuse of built knowledge in order to facilitate the decision making process and, ultimately, to increase the performance of the cognitive radio system.

Efficient flow of information is essential for quick and effective decision-making. The notion behind Knowledge Management is to structure the flow of information throughout the system so that the learning of one network entity within the system is passed on to others and is available to the system even if the given entity is not active. Knowledge Management also involves consolidating and storing data and presenting it in a way that will be suitable for future exploitation. Figure 1-1 depicts the generic steps in the Knowledge Management process.

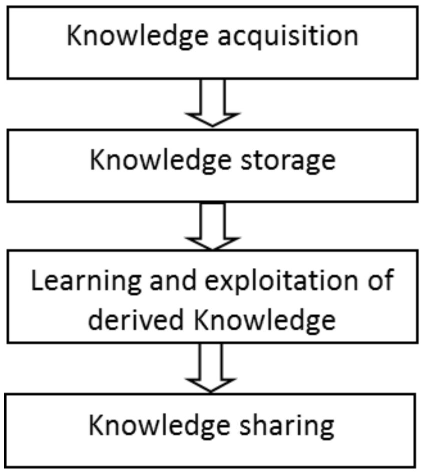

Figure 1-1: Knowledge Management process

This document focuses on the **acquisition** and **storage** steps of the Knowledge Management process. The first step in process of obtaining the required knowledge would be to identify that a certain part of information disposes useful data that can be utilized as knowledge, i.e., the knowledge acquisition process. Then, this information should be effectively collected/ stored, and offered to the system enabling its transformation into aggregated knowledge and experience, i.e., the knowledge storage process. Moreover, the document also focuses on designing knowledge models that consist of information inferred in a radio network system using sensors, actuators, as well as other forms of information gathering and acquisition algorithms.

The document is structured as follows. Section 2 elaborates on the identification of information that can be utilized for the process of building knowledge. Section 3 relates to the work elaborated upon in [1] and discusses the processes of acquisition and storage of useful information. Section 4 gives an insight into the developed knowledge models for cognitive networks, while Section 5 concludes this document.

2. Identification of knowledge based useful information

It is vital to identify the area and scope of interest prior to defining the information as useful within the process of obtaining knowledge. This section focuses on the meaning and the type of knowledge that can be built with respect to terms such as user profile, device profile, network capabilities, operator/regulator policies, etc.

Regarding the performance of the cognitive network systems, the network and device management should take into account four important information aspects upon which knowledge can be built/ exploited and learning mechanism can be applied on. These aspects comprise:

- Network users,
- Terminal devices,
- Network capabilities, and,
- Operator/regulator policies, i.e., rules that come from the network operator/ regulator and that should act as constraints within the network.

Specifically, the users' satisfaction of a given network is guided by their own preferences regarding the offered services as well as their own performance. Thus, network management must take into consideration the type of services and the level of performance (quality) that the network provides to the end users. Moreover, the network management system must have the ability to efficiently choose the required device and network configuration for achieving the required performance of the active services while being compliant with the policies of the network operator and/or regulator. Thus, these aspects must also be taken into account when developing cognitive network management systems.

As a result, mechanisms that would build knowledge on the user and the device profiles, the network capabilities and the policies are expected to facilitate the management of the systems. Table 2-1 summarizes the main information types and issues that are addressed when referring to the knowledge building process on the elaborated aspects.

Learning/ Building knowledge on	**Type**	**Explanation**
User information/profile	Utility volume	Utility volume for the use of a service at a particular quality level (Quality of Experience (QoE))
	Price	The maximum price that the user is willing to pay in order to use certain services at specific QoS (Quality of Service) levels, i.e., for a certain QoE
User terminal profile	Terminal configuration	The terminal configuration is related but not bounded to the following aspects: Supported Radio Access Technology (RAT) interfaces (e.g., Long Term Evolution (LTE), WiFi, etc.)

		Associated carrier frequencies and channel bandwidth Transmission power levels
	Supported services and QoS	Different types of services as well as different QoS levels can be provided to the user based on the terminal configuration capabilities. *E.g., High speed packet service can be provided by terminals with wideband channel capabilities.*
Context information and/or Network capabilities	Achieved capabilities	The most likely capabilities (in terms of QoS parameters, such as bit-rate), that can be achieved by a given configuration, in a given location, time zone, etc.
	Future actions	Future situations given a certain situation in the current time zone
	Proactive handling of circumstances	Identifying and mitigating the impact on the circumstances in system even before they occur
Policy	Policy rules	Rules that describe the constraints, permissible options, for terminal configuration and service adaptation
	Supported services	Services supported by a certain terminal configuration
	Reward and punishment	Reward and punishment coefficients for the selection of a certain configuration by a certain transceiver of the device

Table 2-1: Information types for building knowledge

The process of building knowledge, i.e., learning, is also tightly related to the decision making process introducing the aspects of self-awareness and self-management of the cognitive system. Therefore, the mechanisms that build knowledge based on the *system's decision behaviour* must take into consideration the following information aspects:

- Decision reliability,
- Decision time,
- Stored information,
- Situation identification and
- Solution evaluation.

The decision reliability aspect provides information to the knowledge mechanism about the behaviour and efficiency of the decision engine. It gives an insight of how effective the decision has been for the given circumstances and can be utilized to increase the overall performance of the decision engine for future actions.

Another parameter highly related to the decision engine performance is the time required for reaching a decision, i.e., decision time. Cognitive radio networks and dynamic spectrum access are characterized with highly dynamic scenarios and require specific time constraints in terms of the spectrum access and activation of the communications services. Thus, lowering the decision time is of outmost importance for the performance of the cognitive network.

Recordings of the system behaviour (recording/storing of information on encountered situations, actions that were taken in reaction to these situations and information on the effectiveness/efficiency of the actions - decisions taken etc.) can have valuable impact on the overall decision engine performance when exploited by learning processes and knowledge mechanisms. One example is the identification of similar contextual situations. In this case, the knowledge mechanism utilizes the stored information in order to derive whether a previously selected and enforced action should be applied directly without the need of executing a new decision making process.

Type	**Explanation**
Decision efficiency	The learning process focuses on two generic parameters: • Decision reliability • Decision time
Situation (case) identification	Identification of similar contextual situations, so that it can be derived whether a previously selected and enforced action should be applied directly without the need of executing anew the decision making process
Solution evaluation	Evaluation of enforced solutions and recording of the result of this evaluation along with the relevant context information

Table 2-2: System's decision behaviour information types

Solution evaluation is another knowledge based use case where the stored information can provide the necessary information to the learning mechanisms in order to improve the performance of the decision making process. Namely, the evaluation of the enforced solutions as well the result (conclusions) of this evaluation along with the relevant context information (based on which the conclusions were made) can be used to determine the performance of the decision making mechanism and investigate the possibilities of its possible performance enhancements.

Table 2-2 summarizes the cognitive radio system’s decision behaviour information types discussed above.

After scrutinizing the essential aspects of the meaning and the type of knowledge that can be built within cognitive radio systems, the following section will focus on the acquisition and storage processes.

3. Information acquisition and storage

This section provides a brief overview of the information formats and methods for information acquisition elaborated upon in [1], and gives insight into the possible data formats and structures related to the information storage process.

3.1 Methods for information acquisition

Different types of information sets require different approaches and methods for its acquisition. Based on the scenarios elaborated in [1] (i.e., "Knowledge based management of reconfigurable B3G infrastructures", "Self-optimization of cognitive user devices" and "Cognitive systems and opportunistic networks"), this section focuses on presenting how information is acquired for building the required knowledge regarding the user information, context information and policies.

3.1.1 User information acquisition

User information includes all the information that constitutes a user profile. As a result, user information is comprised of the currently running services/applications, corresponding QoS levels, location, time zone and provided user feedback. This information can be obtained directly from the user device.

One of the most suitable approaches for exploiting the user information acquisition is the Bayesian networks [1]. However, this is not the case for the satisfaction of the user with respect to the supported services. This aspect yields user's feedback and, therefore, the following process is usually undertaken. The user initiates a specific service. At the initial stages, i.e., when there is not enough feedback received by the user yet, it is assumed that the user does not have any particular preferences and thus is indifferent between service provision choices. As a result, configurations are selected according to the context (location and time zone) and the operator/regulator policies. After the use of the service, the user is asked to provide a rating, which corresponds to how much he liked the particular service provision, on a "Likert Scale" [2], which includes five different rating options. These rating options are: 1 for awful, 2 for poor, 3 for OK, 4 for good and 5 for excellent. In this way, even non-technology expert users can provide the system with feedback on their preferences. The user is also given the choice to decline providing a rating.

3.1.2 Context Information acquisition

The term context information refers to the information that is related to the status of the network, the user and the associated terminal device. Moreover, it provides information on their environment. This kind of information can be acquired through monitoring and discovery procedures. Various machine learning concepts like Bayesian networks, Neural Networks and Self-Organizing Maps can be utilized in order to efficiently acquire the required context information [1].The context information can be also exchanged among network or user devices through awareness networking via Cognitive Pilot Channels (CPC) and/or Cognitive Control Radio (CCR) [1]. The monitoring procedures provide information on the current configuration. They expose the QoS level in each communication layer as well as interlayer aspects, e.g., the assignment of applications/services to transceivers. The discovery procedures provide information on the alternate configurations available in the area.

3.1.3 Policy acquisition

Policies designate rules and functionality that should be followed in context handling. Sample rules can specify allowed QoS levels per application, allocations of applications to Radio Access Technologies (RATs) and assignments of configurations to transceivers. Acquiring policy information refers to the functionality of the device to obtain policies such as spectrum/network policies from the CPC or local spectrum usage policies from the CCR. More details in terms of the policy acquisition can be found in [1].

3.2 Methods for information storage

Correct storage of the gathered information can play a crucial role in the process of obtaining knowledge. This section elaborates on the formats and structures of the stored data and its relation to the collected information that reflect the behaviour of the given network. As discussed in the previous section and argued in [1], there are multiple types of information that may be used for building knowledge varying from user preferences, policies, assessment of efficiency of decisions to context information. This may further include information on available frequency bands (or RATs), interference levels, transmitter locations propagation information etc.

Based on the aforementioned types of information, diverse types of information storage may be utilized. The concept of Radio Environment Maps (REMs) offers vast possibilities in terms of the information storage in cognitive radio networks. The exploitation of REMs can allow cognitive systems to obtain knowledge of their environment regarding the storage of user, context and policy information, in a cost-efficient manner. The remaining part of this section will focus and elaborate on the REM information storage type referring to it as the REM Database (RDB).

The RDB is the main storage for the collected data in a given cognitive system. It should be able to store data coming from different types of actuators (e.g., spectrum sensors, user terminals, system administrators, etc.) associating the stored data to the type of the device and configuration used to perform the information gathering. The RDB should constantly keep track of the active actuators in the network and their current configurations dynamically controlling the collection process. Therefore, the RDB should be able to query the actuators to make reconfigurations and perform specific information gathering processes when needed. The RDB data can be dynamically used by different mechanisms (e.g., decision making mechanisms, knowledge building mechanisms etc.). The processed data can be sent back to the RDB for storage and possible subsequent usage. In terms of the data management and storage aspect, the RDB should take into consideration, but is not bounded, to the types indicated in the following subsections.

3.2.1 User information

The user information type should store the data reflecting the capabilities and features of the active devices in the cognitive network. Table 3-1 denotes an example of the user information data storage model in terms of its sub-types and their elements.

Sub-Type	**Element**	**Comment**
User Type	Incumbent or Secondary	The user type information can be important for many scenarios where a distinction between the PUs and SUs types is needed.
	Type of incumbent/secondary	
User location	Based on coordinates	This type of location information can be used in cases where the exact location of the user is needed, e.g., opportunistic spectrum access.
	Based on regions	This location information denotes the region in which the user is located. Can be useful in scenarios like femto-cell deployment and TVWS/ opportunistic networks scenario.
User configurations	Transmit power	Useful for the case of opportunistic spectrum access, secondary spectrum sharing, etc.
	Operating frequency	The operating frequency gives insight of the spectral characteristics of the user. Can be utilized by variety of processes, e.g., white space calculation, secondary spectrum sharing etc.
	Supported RATs	The type of interfaces supported can give crucial information about the network capabilities of the device.
User services	Supported services	The elements give insight of the characteristics of the user devices in terms of the supported services and the sets of QoS levels associated with the given services.
	QoS levels	

Table 3-1: User Information

3.2.2 Transmitter information

This information type should store the data concerning the type, location, transmit power, operating frequency and service area of the transmitter. Table 3-2 denotes an example of the transmitter information data storage model in terms of its sub-types and their elements.

Sub-Type	Element	Comment
Transmitter Type	Incumbent or Secondary	The transmitter type information can be important for many scenarios where a distinction between the transmitter types is needed.
	Type of incumbent/secondary	
Transmitter location	Based on coordinates	This type of location information can be used in cases where the exact location of the transmitter is needed, e.g., path loss estimation.
	Based on regions	This location information denotes the region in which the transmitter is located. Can be useful in scenarios like femto-cell deployment and opportunistic networks scenario.
Transmit power	Maximal transmit power	Useful for calculation of service areas and propagation models
Operating frequency	Centre frequency	The elements give insight of the spectral characteristics of the transmitter. Important for path loss estimation. Can be utilized by variety of learning and decision making processes, e.g., white space calculation, secondary spectrum sharing etc.
	Bandwidth	
	Spectrum mask	
Service area	Type of metric (RSS (Received Signal Strength), SINR (Signal to Interference-plus-Noise Ratio), bit rate, etc.)	Important for the case of TVWS use cases and opportunistic networks scenario.
	Result (polygon, pixel image)	

Table 3-2: Transmitter Information

3.2.3 Radio Interference Field (RIF) information

The Radio Interference Field (RIF) information type should store the data concerning the RIF estimation and frequency range. Table 3-3 denotes an example of the RIF information data storage model in terms of its sub-types and their elements.

Sub-Type	Element	Comment
RIF estimation	Pixel image based	The pixel image representation requires the *dimension* and *resolution* of the estimated RIF. The basis function representation requires the *type of basis function, number of basic functions*, *corresponding function arguments*. Regardless of the representation type, the RIF estimation can be exploited variety for variety of processing tools like fitting of propagation models, estimation of coverage areas, detection of coverage holes, etc.
	Basis function based	
Operating frequency	Central frequency	The operating frequency gives the insight about the location of the RIF in the spectral domain.
	Bandwidth	

Table 3-3: Radio Interference Field (RIF) information

3.2.4 Propagation information

The propagation information type should store data regarding the propagation model, environment and area dimensions. Table 3-4 denotes an example of the propagation information data storage model.

Sub-Type	Element	Comment
Propagation model	Type of propagation model	Carries the information about the model type and its parameters (e.g., indoor/outdoor, terrain type etc.)
	Area dimensions (latitude/longitude)	Every propagation model should be associated with an area of interest defined as a polygon with given longitudinal and latitudinal

		coordinates. This notion defines the spatial applicability of the given model.

Table 3-4: Propagation information

3.2.5 Spectrum usage information

The spectrum usage information type should store data concerning the activity of the transmitters in a given area of interest. Table 3-5 denotes an example of the Propagation information data storage model.

Sub-Type	**Element**	**Comment**
Transmitter activity	Duty cycle	The category includes the duty cycle and the distribution of the received signal from different transmitters at a given point of interest. This information can be used for localization purposes as well as for improved handover management and user density estimation.
	RSS distribution	
Area size	Area dimensions (latitude/longitude)	Every spectrum usage model should be associated with an area of interest. This notion defines the spatial applicability of the given information type.

Table 3-5: Spectrum usage information

3.2.6 Spectrum sensor information

The spectrum sensors represent one of the most exploited actuators in the context of the cognitive systems. Table 3-6 denotes an example of the stored actuator information based on the spectrum sensor data storage model.

Sub-Type	**Element**	**Comment**
Sensing type	Sampling type (RSS, I-Q (In-phase Quadrature))	The diverse spectrum sensor capabilities can be exploited in different scenarios. For example, feature detection can be utilized for transmitter type identification, while energy based detection can be used
	Detector type (RMS (Root Mean Square), Max Hold, Mean Hold, Min Hold)	
Sensing configurations	Resolution bandwidth	

	Sampling frequency	for RIF and propagation estimation.
	Operational bandwidth	
Detection methods	Energy based detection	
	Feature detection	
Location	Coordinates	The location of the spectrum sensor provides crucial information for process like RIF and propagation model estimation.

Table 3-6: Spectrum sensor information

3.2.7 Radio Access Technology (RAT) /Operator information

This type of information should store data concerning the about available radio access technologies and operators in a given area of interest and their corresponding features and capabilities. Table 3-7 denotes and example of the RAT/ Operator information data storage model.

Sub-Type	**Element**	**Comment**
Operator information	Available operators	List of operators available in the vicinity of interest.
	Price	List of prices related to the different types of traffic profiles of the operator of interest.
	Services	List of supported services at the given operator of interest.
RAT information	Available RATs	List of RATs available in the area of interest.
	Operating frequency	List of operating frequencies for the given RAT of interest.
	Operational bandwidth	List of supported bandwidths for the given RAT of interest.
	Max. bit rate	Maximal bit rate supported for the given RAT of interest.
	Coverage area	List of cells and their coverage area for the RAT of interest.
	Average load-level	List of cells and their average load-levels (short-term, long-term) for the RAT of interest.

Table 3-7: Radio Access Technology (RAT)/Operator information

Depending on the type of information and how/ where this information is exploited, storage of information may be addressed differently. As discussed in [1], based on the scenarios and use cases, the information can be stored either locally (e.g., mobile terminals or Points of Attachment) or globally (e.g., in a centralized storage entity). In order to increase the systems' flexibility and responsiveness the RDB should comprise hierarchical storage architecture. This approach implies that specific sub-sets of the acquired information would be stored in different layers of the RDB by exploiting the process of data replication. For example, consider the RIF information data management in a case of a femto-cell scenario, where the RDB is deployed at the HeNB (Home e-Node B) and eNB (e-Node B)level. The HeNB RDB will store the RIF information regarding its surrounding environment only, while the RIF information at the eNB RDB level would utilize the data stored in all of its underlain RDBs (i.e., HeNB RDBs).

Based on the analyses in sections 2 and 3, the following section will discuss in details the knowledge models applicable for cognitive radio networks.

4. Knowledge models for cognitive networks

The knowledge models represent a set of information inferred in a radio network system using sensors, actuators as well as other form of information gathering and acquisition algorithms. This section focuses on designing knowledge models that consist of the highest level of information acquired and required in the case of cognitive radio networks. The knowledge models aim at capturing various aspects, e.g.:

- Status of the node of the system,
- Status/behaviour of the network and the environment,
- Status and features of the network and the users/terminals etc.

Knowledge and knowledge models have to be stored, maintained and disseminated either via an active or passive access mechanism. Depending on whether terminals, devices or nodes actively request radio environment knowledge or passively wait until it becomes available, there must be some function to gather and refine the knowledge. Similar approaches have been pursued in projects dealing with context aware service creation (e.g., S4ALL [3], m:Ciudad [4] and others) defining a "knowledge warehouse" in which information about services and their capabilities, availability and use are derived and stored. The approaches are built upon knowledge inference, search, discovery and learning mechanisms. A similar approach may be used to generate and disseminate radio environment knowledge that can facilitate the decision making processes for cognitive radio devices. This section elaborates on a number of knowledge models, which directly or indirectly relate to the cognitive radio system learning process. It starts with a brief discussion of the aspects of knowledge management in relation to cognitive radio systems bridging the gap between the information acquisition/storage process and the development of the knowledge models.

4.1 Knowledge and Knowledge Management for support of Cognitive Radio (CR) devices

The essential component of the knowledge management for Cognitive Radio (CR) devices is the understanding that radio environmental knowledge is not a product of spectrum sensing only. Deriving such knowledge may also depend on information about the type of device, characteristics of transceiver and other influencing aspects depending on the level of granularity and required precision. This subsection discusses the fundamental functions needed in a more generic knowledge management structure.

First and foremost, the fundamental knowledge management functions must comprise functions that allow *referencing external ontologies* and functions that allow *maintenance of domain specific ontologies*. The former ones are used to associate content and device (or equipment) descriptions to domain knowledge represented in terms of domain ontologies, whereas the latter ones foster easier management of different ontologies (e.g., they may be country specific or even down to individual providers). Additionally, there needs to be knowledge management functions that allow *creation of a new environment description* whenever changes to the environment occur. Also, there is a need for *ontology matching support* that fosters management of the relationship between descriptions stored in knowledge management and other related ontologies that may be used on a temporal or permanent basis. Furthermore, the knowledge management functions should comprise *search functionality* in order to cover the various aspects that may need to be searched in a knowledge base (e.g., search for concepts, i.e., class or attribute, that match a given set of tags, search for capabilities and the semantic description, search for capabilities, based on input/ output constraints or terminal brand/ model, search for existing content structure based on tags, search for U+ Services based on various criteria etc.). Finally, the knowledge management functions should provide *consistency checking* in order to support the integrity and coherence of the knowledge base and community-driven ontologies.

Knowledge management in Cognitive Radio Systems (CRS) predominantly will handle and process the various ontologies that are used to describe the radio environment of devices or aspects that may influence the radio environment.

4.2 Ontology for service modelling and reasoning

In computer science, the term *ontology* is used to specify a conceptualization [5] in the context of knowledge sharing. The conceptualization refers to an abstract, i.e., simplified view of the environment that needs to be represented. Every knowledge base explicitly or implicitly uses some sort of conceptualization. Ontologies can be used to set a vocabulary of a certain domain as well as describe its main concepts and relations between them. Various logical operations can be carried out on the item of the ontology. A correctly formulated ontology allows for checking and guaranteeing consistency of the performed logical operations, but it does not consists of the complete “stored” information with respect to queries and assertions formulated using the vocabulary defined in the ontology. Often the ontologies are used along with a database and a reasoning engine in order to constitute a knowledge base that can employ the description logic, which performs deductions on the consistency of the knowledge model and fills in the missing gaps in the logical constructs.

In cognitive networking, there is an immense need for common vocabulary in the communication between the different entities as well as the different protocol layers. Also, there still exists a need to link concepts on the lower protocol layers, e.g., relate frequencies on which typically Dynamic Spectrum Access (DSA) algorithms operate to physical and logical channels of the underlying technology (a term used by such standardized devices as IEEE 802.11af WLAN enabled nodes). Additionally, the policy restrictions are natural to be realized through ontology and related reasoning engines [6]. However, ontology could bring even more benefit when used to harmonize control plane concepts across multiple protocol layers and logical domains, as there exists multiple inconsistencies in the respective terminologies and their harmonization is required to truly enable the Knowledge Plane/ Cognitive Networking visions [7] - [9]. For example, one variant of the ontology approach for cognitive radio has been already proposed and standardized [10]. Other approaches can be found in [11].

This section considers an aspect of the outlined problem that is not typically discussed in the cognitive domain, which is the high-level service harmonization. It is apparent that in the co-existence scenarios it is important to ensure that not only users share the frequency pool and other network resources as defined by (sometimes very complex, e.g., utility-based [12]) policies, but they also obtain the required *services*. In this case, it is needed to identify the *interdependencies* between the relevant services hosted by heterogeneous devices in a network, so that the management framework can enforce their consistent performance and maintenance. As an example, this section considers scenario for ensuring the consistency of performance of services installed on the *white appliances* that are deployed in the *home* *environment* and wirelessly connected to the gateway [13]. It is assumed that there is a possibility to build a central knowledge base that can reason on services deployed on these devices identifying inconsistent setups and correcting these failures through the corresponding software updates. For a network resource restriction, it is adopted that there is only a certain bandwidth available for sharing at a certain time instance. The core of the knowledge base in this scenario is the ontology, which is designed with additional plug-ins and functionalities that the native ontological reasoner based on the *description logic* cannot perform (for example, quantitative comparison).

For realization of the proposed knowledge, the Web Ontology Language (OWL) has been utilized [14] that is part of the collaborative research effort led by W3C (World Wide Web Consortium) toward establishing the Semantic Web. The aim of the Semantic Web is to provide a common framework for information sharing and use across multiple applications, communities and devices. OWL is based on XML (Extensible Markup Language) and allows definitions of the following logical operations:

- Relations between classes (e.g., disjointness or inclusion),
- Equivalence of classes and
- Different characteristics of properties (e.g., symmetry or transience).

OWL has been chosen to realize the context model of the home environment for several reasons. OWL DL (Web Ontology Language Description Logics), a sublanguage of OWL (exploited in this section), possesses the maximal expressiveness while retaining computational completeness compared to other ontology description languages such as RDFS (Resource Description Framework Schema) [14] or other OWL modifications. The alternative language, i.e., CoRaL (Cognitive Policy Radio Language) [15], is very domain specific and is mostly utilized for spectrum management. Moreover, ontologies specified in OWL DL are reusable and interoperable, i.e., specific ontology context can be reused in multiple domains and understood by different systems, which in turn enables automated reasoning. Finally, OWL is one of the most popular and standardized ontology languages and most likely will become *de facto* standard for the semantic research in the near future.

4.2.1 Example scenario

The initial scenario in the system considers installation and, later, updates of a new device that is a washing machine. First, once installed, the device has to register itself with a home gateway. The gateway (the central management unit for the home environment) has to check if it has the management software for the given device and, if necessary, install it maintaining consistency of the software regarding the device agent of other home deployed devices. The scenario also considers a central management system with a Knowledge Base (KB) located on the Internet, which is responsible for keeping information on multiple home environments and resolving configuration and other conflicts between the respective devices if the home gateway is incapable of doing so. This management system in extreme cases also sends requests for platform managers for manual assistance in problem resolution (a feature that could be easily enabled through reporting of unresolved conflicts by the reasoning engine).The home gateway is also enabled with the possibility to access the software providers and download the required software needed for the normal operation of the home devices. Once the home gateway updates itself with information concerning the new device (e.g., washing machine), its hardware capabilities and default software installed, it propagates the changes in the data on this home environment to the central management system. Later, when a user wants to change something in the installed devices, e.g., install new power management function and advanced washing program onto the washing machine, the central KB will be inquired to estimate the interdependencies for the desired services and establish secure site from which the needed software components could be downloaded and installed. For example, it needs to be ensured that the power management service is compatible with all other devices at the home network so a common power management can be enabled. Another example is the check if a new washing program can be supported by the particular washing machine. For this, the system needs to ensure if the hardware capabilities of the given device are sufficient and if it has installed all underlying services the new program requires such as the basic washing services.

The core of the central KB outlined above is the ontology. The remaining part of the subsection discusses the structure of the ontologies responsible for capturing and establishing the interdependencies between the services provided by a home environment. Figure 4-1 gives an overview of the ontology capturing the home environment while Figure 4-2 depicts a sample screenshot of the home environment ontologies in the Protégé [16]ontology editor and knowledge-base framework. As seen from the figures, the ontology mainly includes the description of the devices installed at home, the service and the software that realized these services. Additional classes describe, for example, **'events'** encountered by devices or contain **'user'** profiles. There are also multiple subclasses that are not shown in the basic ontology diagram on Figure 4-1 and Figure 4-2. They are derived based on the rules imposed onto the ontology. For example, subclasses of the **'device function'** and **'software service'** classes, Figure 4-1, record all the functions and the corresponding services that a washing machine of a certain type might perform or host. They also allow autonomous deduction of services that have to be additionally installed on these devices. Such reasoning is enabled through the inference engine, FaCT++ [17].

In order to support (i.e., enable) the creation of the previously mentioned subclasses and quantitative reasoning, this work has developed novel modules, using Java or employing Java-compatible interfaces, which are not originally supported by the standard description logic. Protégé, FaCT++ and Jena library [18] are utilized for the realization of the knowledge base. In order to simplify the ontology maintenance, the work elaborated in this section introduces a hierarchical property structure with a number of parent, i.e., abstract, properties. These properties are inherited by child properties that keep the domain or range of the master property as well as its name.

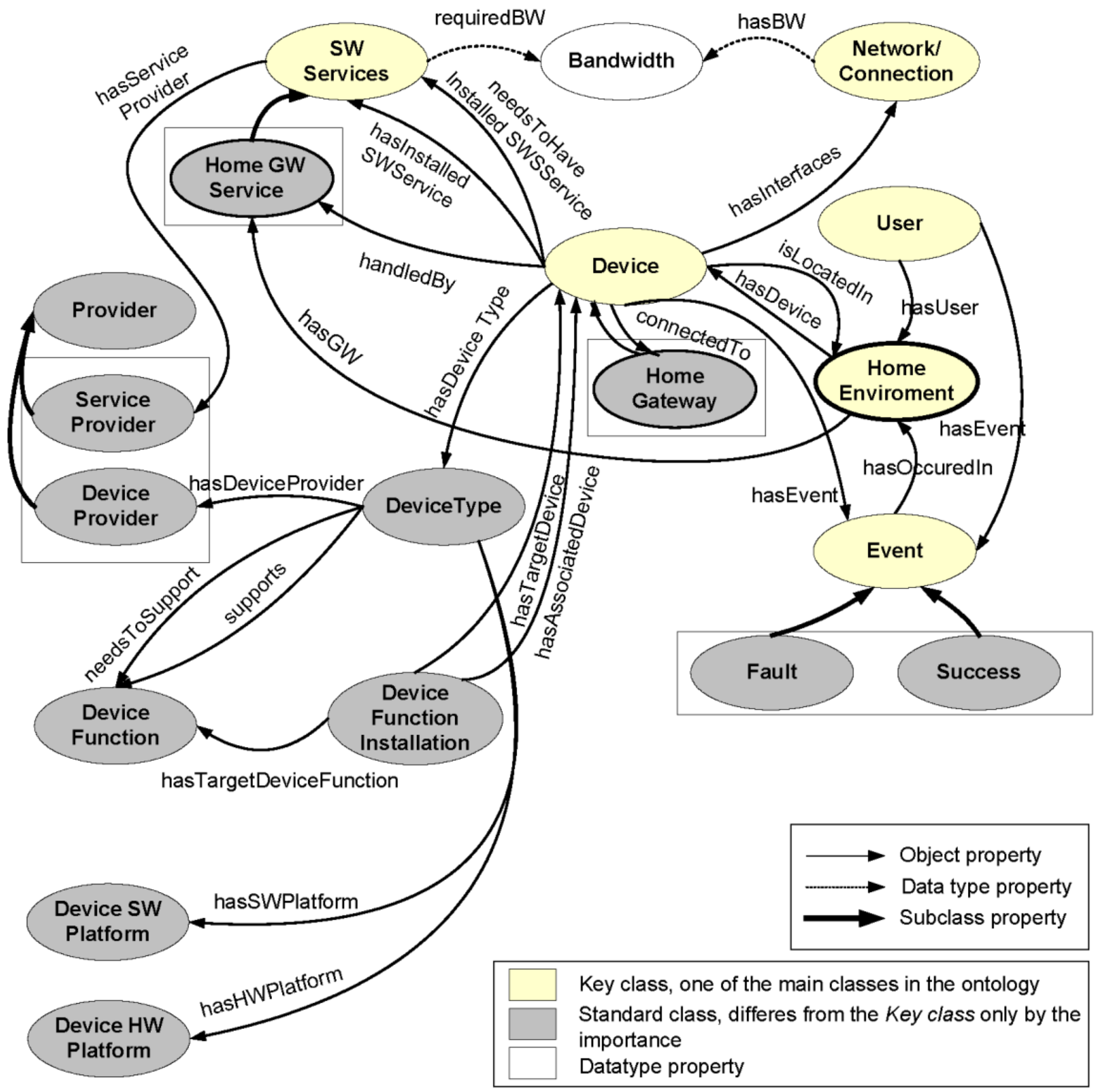

Figure 4-1: Overview of the ontology capturing the home environment

One of the main entities of the proposed ontology is the **'home environment'** class that provides data concerning the users of the home environment and all the devices installed at home. The families of **'device'** and **'service'** classes represent devices and services installed at the home environment. The home gateway device and respective service classes are derived separately as they need to host additional properties that are not required for ordinary devices. The profile of the device includes:

- Device model/type,
- Link to the event depositary,
- List of functionalities and the respective software services that it can provide or wants to install and
- Link to the gateway that handles the appliance.

The classes and properties aiming to capture complex interrelation between its entities are realized following the OWL-S ontology [19] that allows for flexible and rich set of object interdependencies. One example of such reasoning for installation of a new program onto the washing machine is shown in Figure 4-3.

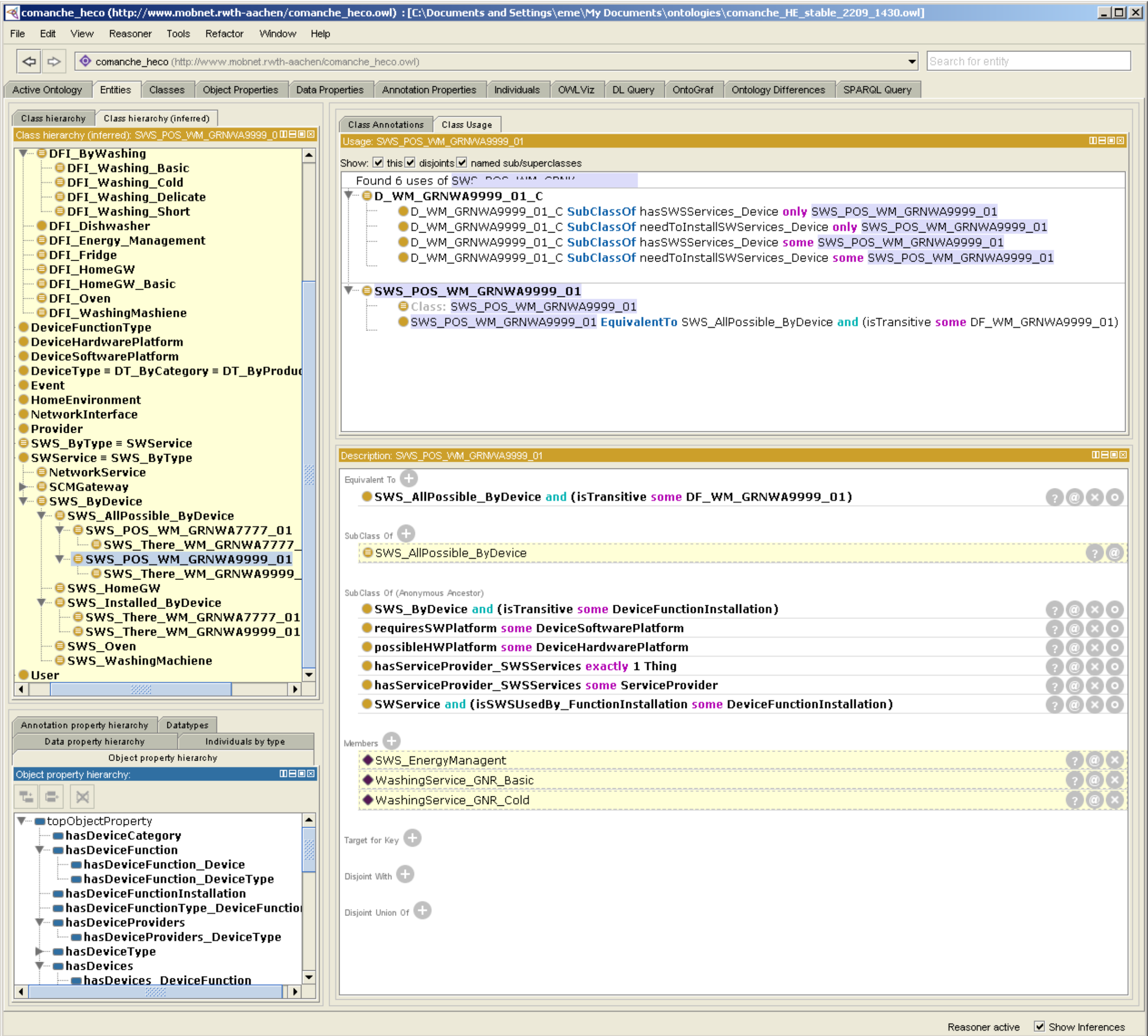

Figure 4-2: Sample screenshot of the developed ontology in Protégé. Yellow boxes on the left highlight inferred classes and entities (object). Among other, they display inferred services that can be possibly installed onto the particular washing machine.

In order to determine if a service can be installed on a certain type of device, the hardware and the software profiles of the device have to be stored, which is enabled through the **'device software'** and the **'hardware platform'** classes. They capture such parameters as RAM, ROM, processing capabilities, peripherals, User Interface (UI) capabilities etc. The **'network interface'** class is used to specify the network capabilities of the specific device type and information from instantiations, which are used to schedule the order of servicing of different nodes/devices in a network. Additionally, through the provider classes (**'service provider'** and **'device provider'**), the system can obtain the list of companies where hardware and software modules, could be installed, and device producers could be enquired to the list of trusted provider entities. The **'event'** class keeps statistics on events occurring in the home environment in terms of keeping track of the proposed actions and their outcomes. This information could be used to schedule further actions and to resolve arising conflicts.

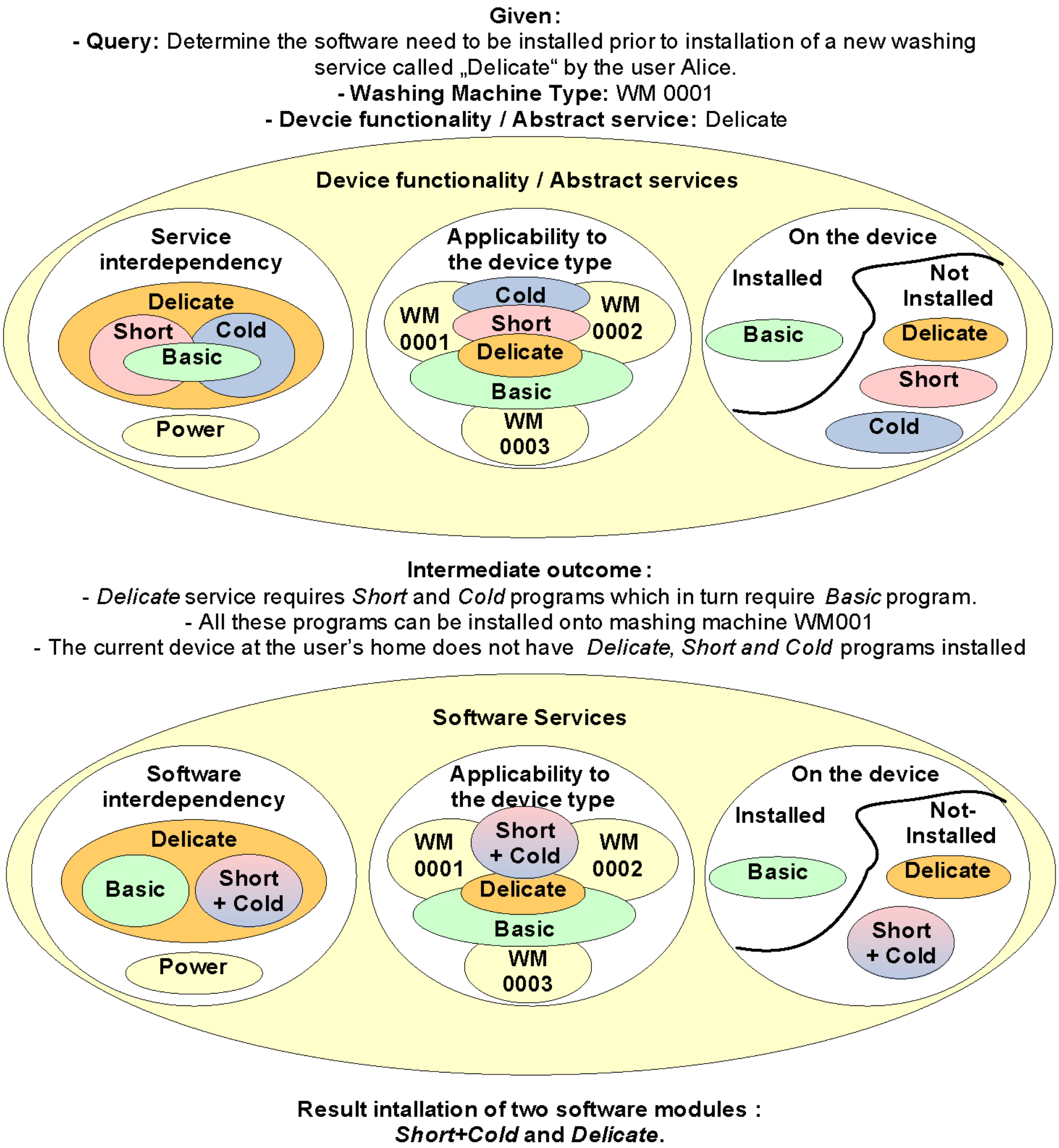

Figure 4-3: Example of the inference performed using the proposed ontology

Overall, the proposed ontology results in rather complex structure that includes, besides the upper level classes described above, also numerous automatically generated subclasses and multiple rules that dictate distribution of objects/ instances between the classes. The suggested ontology is able to install and manage both abstract services and the respective software on the home devices ensuring secure and conflict free functioning of the home environment. This developed KB also responds to changes in the home environment by updating old or installing new services resulting in a seamless configuration of the home network. Additionally, the system allows keeping track of the events happening in the home network in order to provide the possibility for keeping updates of the status of the devices (e.g., to assist the software/hardware providers in the remote maintenance of the home).

The described work in relation to cognitive wireless networking indicates that ontology enabled knowledge bases and knowledge models are one of the candidate approaches for both establishing a common vocabulary required to realize the cross-domain cross-layer Mitola's vision, as well as enabling reasoning based on description logic [20].

4.3 Mappings between cognitive radio ontologies: Example on graph approximations of wireless network structure

One of the challenges in applying ontological reasoning in cognitive wireless networks is the design or choice of the ontology to be used and its underlying modelling abstractions. This section illustrates some of the issues arising as part of such a choice, focusing on understanding and reasoning about the performance characteristics of the cognitive wireless networks. More specifically, the section explores the relations between *spatial* and *graph based* models of wireless networks as possible knowledge models for cognitive radio networks. Due to the inherently spatial nature of the cognitive radio systems, their performance is fundamentally related to locations of transmitters and receivers. However, reasoning about locations is in general challenging and probabilistic node location models tend to have a high dimensionality making their application in optimization decisions difficult. Graph based models on the other hand are often much easier to deal with, and common optimization problems on them can often be approximated in slightly super linear time. Graph-based models are widely used in the context of fixed networks for routing, load balancing, and many other problems. Many of such models are based on random graphs of different types or graphs constructed as solution to specific performance optimization problems [21]-[27]. Such models are not directly applicable in the wireless networking context, so alternative approaches are needed.

The work elaborated in this section takes a slightly different approach compared to the random graph models mentioned above. It still treats the spatial network models as fundamental ones, but also shows, through extensive simulations as well as referrals to the appropriate literature, that the network performance is often not very tightly coupled to the locations of the nodes or distances between them. Instead, there exist a smaller number of knowledge states the network can be in, which allow modelling of the network behaviour with relatively high accuracy. The proper way to map spatial models into graph models is to define *graph approximations* of spatial models with connectivity and conflict graphs [21] being their most known subtypes, as generalizations of usual random geometric graphs, but with multiple edge types [28]. The work in this section studies the structure of such graph approximations for selected spatial network models using different statistical measures, in particular focusing on occurrence of *small sub-graphs* or *network motifs* [29] of up to four nodes. These have been shown in earlier work, e.g., [30], to suffice in rather accurate performance estimates in Wi-Fi-like networks, without the need to understand the behaviour of larger neighbourhoods.

Figure 4-4 shows the results from measurements of Wi-Fi network performance, i.e., throughput, in a typical office building as a function of the distance between the receiver and the transmitter. It is evident that for smaller packet sizes (i.e., 1KB, 1.5KB) the throughput is rather invariant to the distance, followed by a sharp drop. Clearly, such behaviour could be modelled by using only two discrete states instead of utilizing a spatial model of the whole interval of distances. Similar behaviour can be seen in more complicated scenarios as well (see Figure 4-5 and Figure 4-6). It is clear that all given metrics are again only loosely dependent on the distances between the nodes and therefore the system should be well modelled with a small number of states.

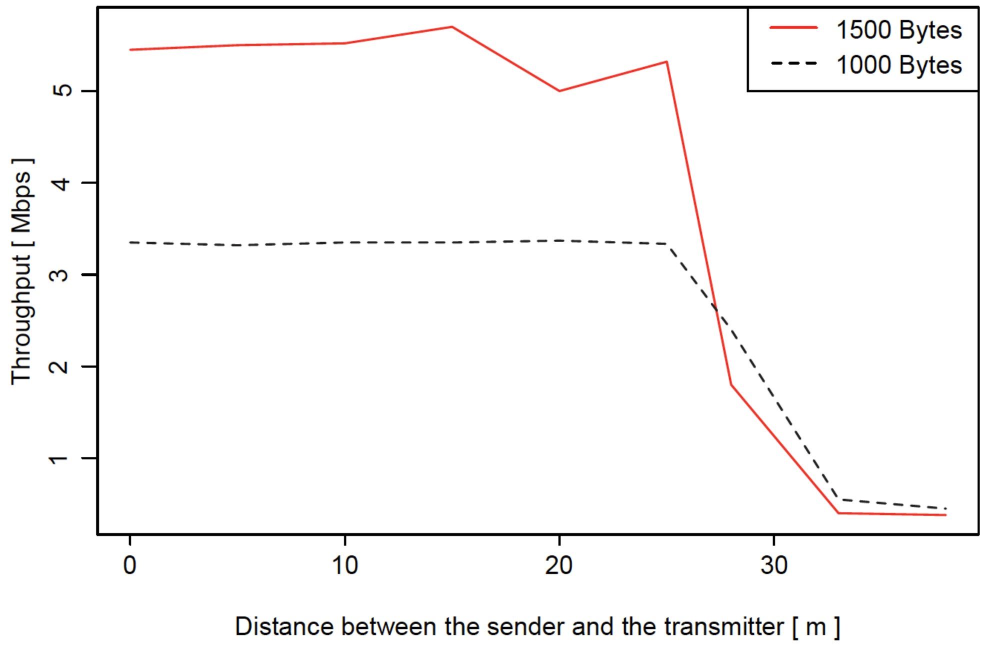

Figure 4-4: Sample UDP throughput in outdoor environment for Wi-Fi link [28][31]. The results are shown for two different packet sizes of 1000 and 1500 bytes.

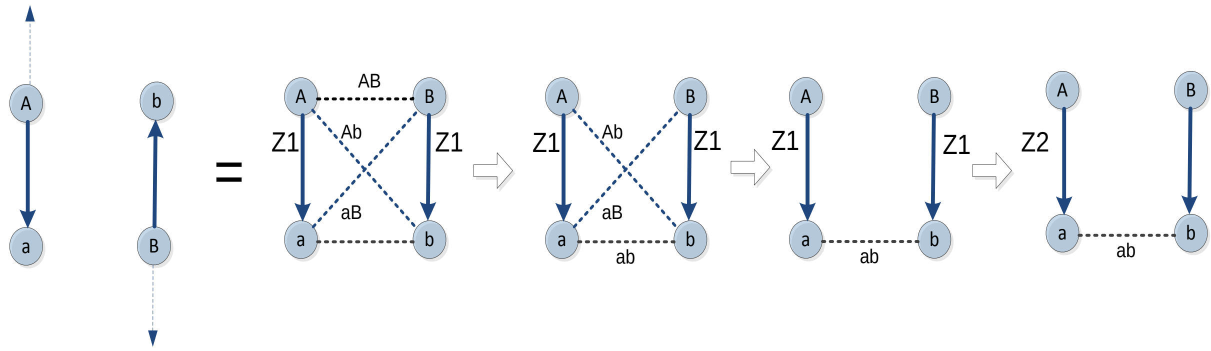

Figure 4-5: Symmetric traffic. Figure on the left shows the initial setup of the nodes with two nodes A and B simultaneously moving from the receivers. Figure on the right displays the corresponding connectivity/ performance graphs.

In the spatial network model, the natural approach is to generalize the usual notion of random geometric graphs, which assign edges between nodes that are closer than a prescribed distance threshold apart. In order to be able to model higher number of interactions, instead of only the edge type, *labelled edges* are assigned between the nodes. The assignment of labels will depend on the application scenario, the knowledge model and the underlying network of interest. For example, for systems based on Carrier Sense Multiple Access (CSMA), edge types would typically be chosen to distinguish between situations in which data exchange is possible and in which data exchange is not possible due to insufficient SINR at the receiver, but in which the carrier sense threshold is exceeded. Therefore, as depicted on Figure 4-7, nodes connected with a first type of edge (Zone1) can communicate with each other in a high performance fashion, the nodes connected with the second edge type (Zone2) communicate in a normal i.e., average mode, whereas the nodes connected with the third edge type (Zone3) cannot communicate, but are capable of carrier sensing.

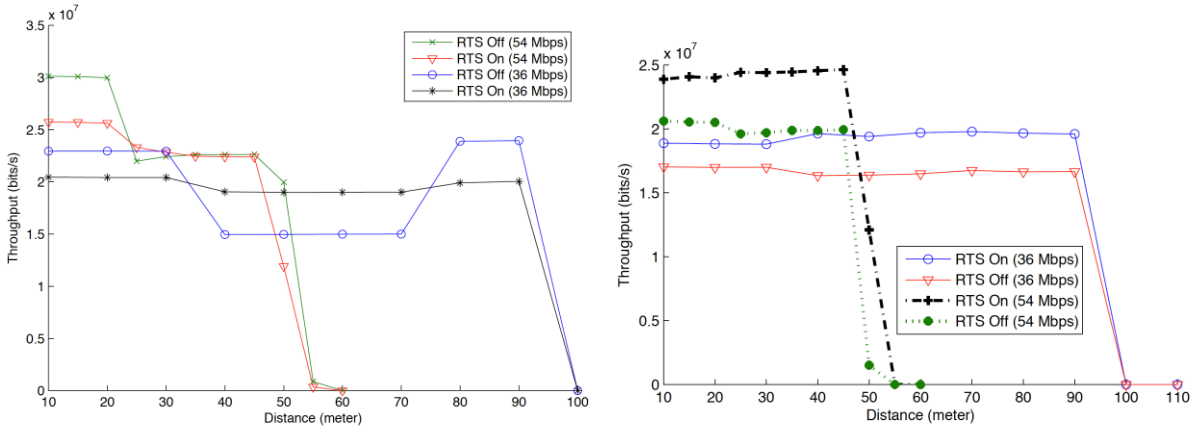

Figure 4-6: Performance achieved for the symmetric scenario for UDP (left) and TCP (right) traffic with respect to changes in the transition rate and the RTS/CTS parameters

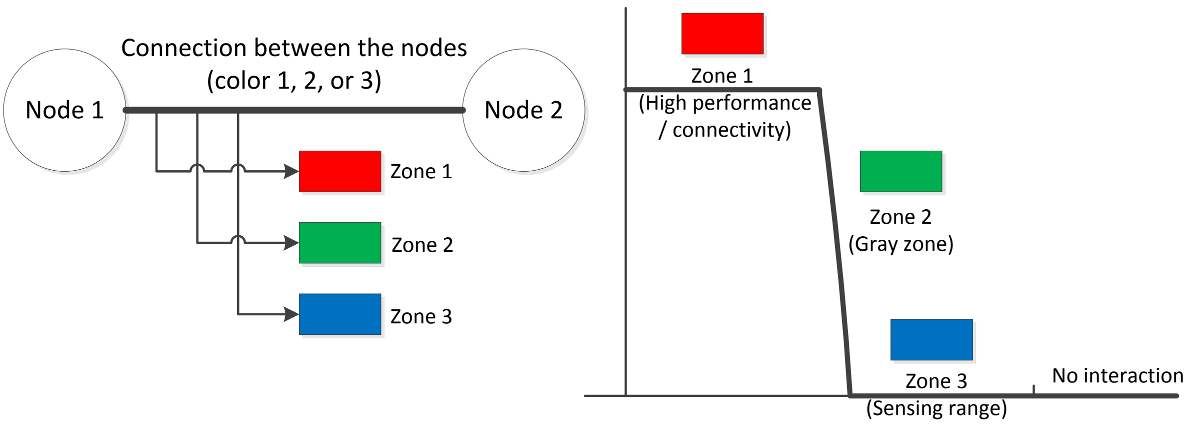

Figure 4-7: Approximation of performance with three values of a graph label

Moreover, the work elaborated in this section studies the influence of the choice of the spatial model on the structure of the arising graph abstractions. Spatial network models are usually formulated in terms of *point processes* [32]. These can be informally defined as random processes assigning the locations X_i of n points into a given region W, where n itself represents a random variable. The most common example of a point process is the *Poisson point process* for which n is a Poisson random variable proportional to the area of W and the locations X_i are uniformly distributed on W in independent and identically distributed (i.i.d.) fashion. Real networks are usually not well described by Poisson point processes. Planned network deployments (such as cellular networks or mesh networks) tend to be more *regular*, i.e., nodes typically are not found to be very close to each other. This work models such network structures by utilizing two distinct approaches:

- **Simple Sequential Inhibition (SSI)** process, generated by sequentially placing nodes on W uniformly in i.i.d. fashion, but rejects placements that are closer than a *predefined distance* Rapart from already placed nodes.

- **Geyer saturation** process, which has been shown to model well variety of network types in [33], [34].

The remaining part of the section focuses on the performance of the location models introduced above in terms of the overall degree distribution of the arising graph approximations for the three spatial models. Figure 4-8 depicts the overall degree distribution of the location models (Poisson, SSI, Geyer) for two scenarios, “outdoor” corresponding to threshold distances of 200 and 400 meters used to define the two edge typesand “indoor”, corresponding to distances of 50 and 100 meters. The parameters of the node location models were chosen to yield on average 270 and 13.5 nodes per square kilometre, respectively. The results in Figure 4-8 evidently show that the underlying spatial model plays a major role in the arising graph approximations, e.g., with respect to the node degree distribution. Therefore, the development of the network knowledge model needs to incorporate proper understanding of the spatial structure and, afterwards, to proceed with the development of graph approximations to reduce the reasoning complexity.

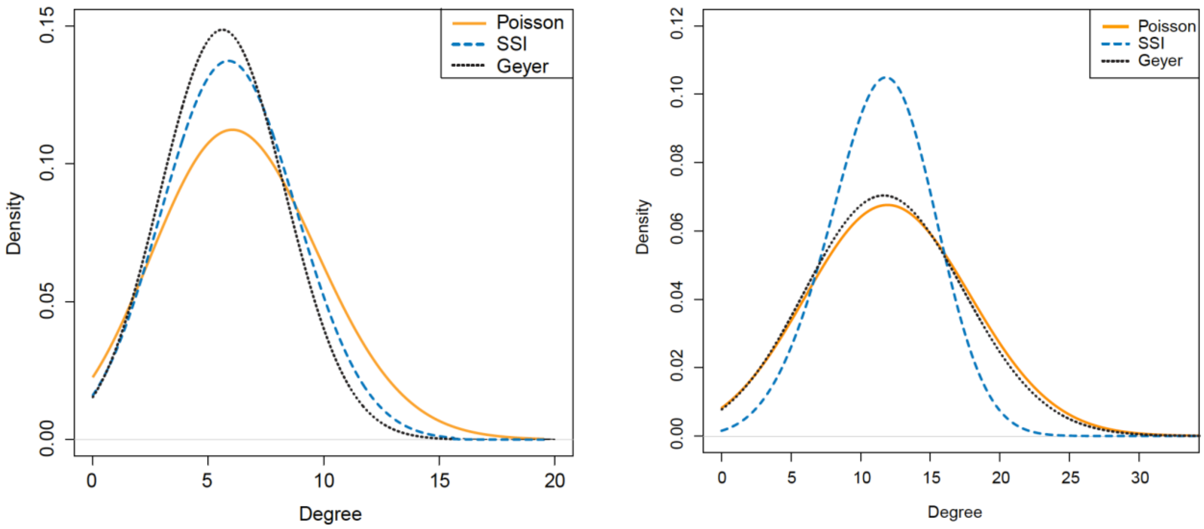

Figure 4-8: The overall degree distributions for the outdoor (left) and indoor (right) Wi-Fi scenarios

While the degree distribution itself is already an informative metric, it is not sufficient for performance evaluation beyond simple metrics such as marginal contention success rate. For more complex metrics, structures of larger neighbourhoods are required. Figure 4-9 compares the occurrence of three-node labelled subgraphs or motifs between two of the spatial network models. It is evident that even for more complicated structures, the underlying spatial distribution continues to play a major role. Moreover, the figure shows that there is a significant amount of “structure” in the arising graph approximations.

The work presented in this section, based on the prior work elaborated in [28], illustrated the relationships between two knowledge model types that can be used to reason about the structure and performance of cognitive wireless networks. The first knowledge model type is the traditional spatial model in which individual locations of nodes are modelled. Such knowledge models can be made highly realistic and used for a variety of reasoning and optimization tasks. Unfortunately, they can also become highly complex and challenging to use for these purposes. The second category of knowledge models discussed is that of the graph approximations of spatial models. These knowledge models are constructed based on an underlying spatial model by quantizing the distances between nodes and using the quantized values as labels on edges of a graph. Based on the measurement and simulation results, it is clear that such quantization can be made in a number of application scenarios without significantly degrading the accuracy of the resulting models. The work also explored the influence of the underlying spatial node location models on the resulting graph approximations and the results showed that the spatial model plays a major role.

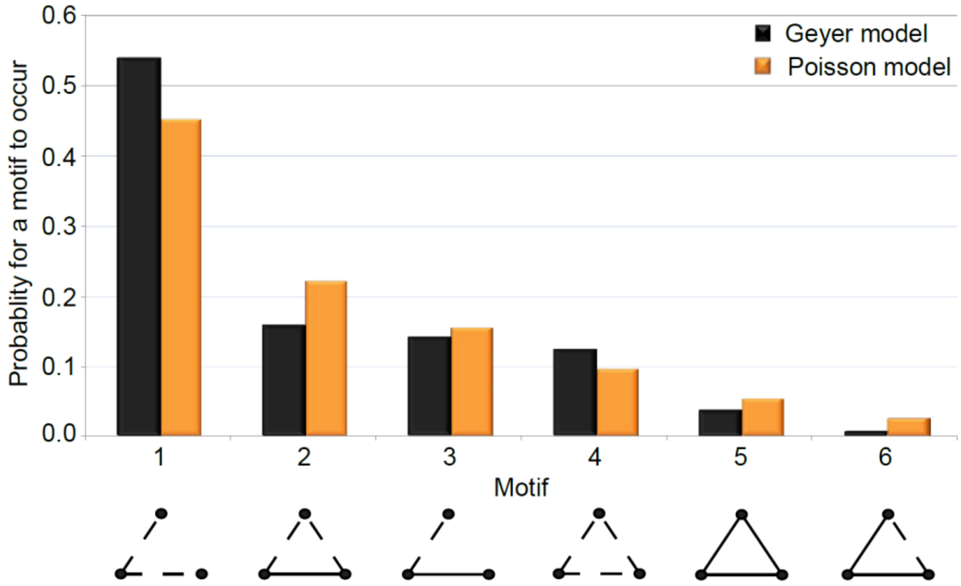

Figure 4-9: The rank-frequency plots for the Geyer and Poisson models for the occurrence of three-node network motifs for the Outdoor Wi-Fi scenario. The illustration of the motifs is given as well. Solid lines denote "connectivity" edges, and dashed lines correspond to "sensing" edges

Generalizing the above observations, these results indicate that for a number of application scenarios it is of interest to develop ontologies or knowledge models in a step-wise fashion. More fine-grained models can first be used to try to capture the physical characteristics of the network, followed by an exploration of the influence of those characteristics on the performance measure of interest. Should these influences exhibit easily quantized behaviours, graph approximations or other types of discrete models can then be derived from the more detailed underlying models to be used for knowledge representation, storage and for different applications at the run-time of the network.

4.4 User profile modelling

When building knowledge on user profiles (either in terms of information or in terms of preferences and behaviour), it is important to have a common understanding of the used parameters. This subsection focuses on presenting these parameters and how these contribute to the accurate representation of the preferences of the user for QoS levels when a certain service is used at a certain location and time of day.

User preferences are expressed through the *Utility Volume*, i.e., a value associated with each application/service and QoS level. A set of user profile parameters, which are related to user preferences, have been defined to guide the configuration of the user equipment. User profile parameters can be split into two categories:

- Observable parameters and
- Output parameters.

Observable parameters are measurable parameters, which can be inferred by the system or provided by the user with the minimum interaction. They include the currently running services/applications, corresponding QoS levels, location, time zone and provided user feedback. For obtaining user's feedback the process below is followed. The user initiates a specific service. At the initial stages, i.e., when there is not enough feedback received by the user yet, the Profiles Management component assumes that the user does not have any particular preferences and thus is indifferent between service provision choices. As a result, configurations are selected according to the context (location and time zone) and the policies. After the use of the service, the user is asked to provide a rating, which corresponds to how much he liked the particular service provision, on a Likert Scale [2], which includes five different rating options. In this way, even non-technology expert users can provide the system with feedback on their preferences. The user is also given the choice to decline providing a rating. The observable parameters and their potential values are presented in Table 4-1.

Observable Parameters	**Potential Value**
Service	Audio, Video, Data, Voice
Quality of Service level	High, Medium, Low
Location	Value retrieved by context acquisition solution
Time Zone	Value retrieved by context acquisition solution
User Role	Personal, Professional (may encompass location and time zone information)
User feedback	1- Awful, 2- Poor, 3- OK, 4- Good, 5- Excellent

Table 4-1: Observable parameters and their potential values

Output parameters depend on the value of observable parameters. Their value is dynamically updated over time. Output parameters are used in the selection process in order to decide on the most appropriate configuration for the specific user in a certain context (location, time zone, user role). In the mechanisms presented above, the only output parameter that was used is the Utility Volume (Table 4-2). However, other output parameters could also be used. Another example of output parameters is the maximum acceptable price that the user is willing to pay in order to be provided a certain service at a specific QoS level.

Output Parameter	**Potential Value**
Utility Volume	$ucxt(s_1,q_1)$, $ucxt(s_2,q_2)$, $ucxt(s_1,q_2)$, …..
Comment: where s_i denotes service i, q_j denotes QoS level j, and cxt denotes context, i.e., a particular combination of location and time zone	

Table 4-2: Output parameters and their potential values

The Utility Volume is used to represent user preferences for QoS levels when making use of a certain service. In other words, the Utility Volume provides a ranking (by order of preference) of service and QoS combinations. User preferences may vary depending on the context and may change over time. Therefore, the Utility Volume depends on a range of context-related parameters as shown in Table 4-2. More specifically, the Utility Volume, apart from the service and QoS level, may be related to the location of the user, the time zone, the user role and the feedback obtained from the user.

4.5 Devices profiles modelling

Device profiles are built upon network and/or user devices context information. The information provided in each context *x* is (Table 4-3 summarizes the mentioned symbols):

- **Current configuration**, $cfg_C(d,t,x)$, of each transceiver, $t \in TRX(d)$;
- **Alternate transceiver configurations**, $CFG_C(d,t,x) \subseteq CFG(d,t)$, that are available in the environment, and therefore are candidate for use in $t \in TRX(d)$;
- **Cost**, $cst_C^{cfg}(d,t,c,x)$, of reconfiguring $t \in TRX(d)$, from $cfg_C(d,t,x)$ to $c \subseteq CFG_C(d,t,x)$;
- **QoS capabilities**, $qos_C^{cfg}(c,x)$, of each configuration $c \in cfg_C(d,t,x) \cup cfg_C(d,t,x)$;
- **Set of applications**, $srv_C(d,t,x) \subseteq APL_C(u,x)$, served by transceiver $t \in TRX(d)$;
- **QoS level**, $qos_C^{apl}(d,t,s,x)$, offered to application $s \in srv_C(d,t,x)$ by transceiver *t* of device *d*.

One of the most crucial parameter for profile modeling of devices is the reconfiguration cost of the given device. It expresses the time and the resources (battery power, memory space) required to change the configuration of the hardware. This covers also the case of software-reconfigurable and cognitive radio transceivers [35]. In this case, this cost is a function of the size of the software modules that may have to be downloaded and installed to deploy the configuration.

Type of parameter	**Summary of the parameter**
$cfg_C(d,t,x)$	Configuration of transceiver, $t \in TRX(d)$ of device d, in context x.
$cfg_C(d,t,x)$	Alternate configurations for transceiver $t \in TRX(d)$, which are available in the environment, in context x, according to the discovery procedures. These are a subset of the capabilities of the transceiver, i.e., $CFGC(d,t,x) \subseteq CFG(d,t)$.
$cst_C^{cfg}(d,t,c,x)$	Cost of reconfiguring transceiver t of device d, from $cfg_C(d,t,x)$, to a

	configuration $c \in cfg_C(d,t,x) \cup CFGC(d,t,x)$ in context x.
$qos_C^{cfg}(c,x)$	QoS capabilities of a configuration $c \in cfg_C(d,t,x) \cup FGC(d,t,x)$, in context x. Each QoS level consists of K parameters.
$srv_C(d,t,x)$	Applications that are served by transceiver t, of device d, in context x. Inter-layer aspect.
$qos_C^{apl}(d,t,s,x)$	QoS level offered to application $s \in srv_C(d,t,x)$ by the transceiver t, of device d, in context x.

Table 4-3: Parameters of a device profile

4.6 Policies

Policies are set of rules that determine the radio behaviour in the network and represent means capable of decoupling the derivation of the rules governing the behaviours of a system from their enforcement. This has become an attractive means to constrain the configuration and decision-making processes within radio networks in order to ensure system manageability and stability without requiring excessive levels of interaction and control. The resulting sets of policies govern the system behaviour providing varying degrees of freedom depending on the circumstances and strategy. Policies may be static over time and space/location or change dynamically and this choice has a major influence on the way in which they are handled. Policies can be supplied from different sources, i.e., *regulators* can express their regulations in terms of spectrum usage, *operators* can enforce their preferences of network resources usage and even *users* are able to apply policies expressing their preferences and requirements. Policies are designed using a specific policy language with its own ontologies (more details were already elaborated in Section 2).

As each of these rules is differently modelled, this subsection provides only an example (more details can be found in [36]). Particularly, a policy that corresponds to the maximum allowed bit rate based on the network and radio environment conditions is considered. Moreover, it is assumed that a set of *Q* policies $NP = \{np : np = 0,1,.....,Q\}$ has been acquired. Considering that the policy for each session *s* is denoted as np_s $(s \in S)$, the total achieved bit rate for each session should be less or equal to the session's policy. Thus, the following restriction should always be satisfied:

$$\sum \left[x_{s,j} br(s,j) \right] \le np_s \tag{4-1}$$

It also holds that a session policy np_s can be greater or equal with the session's user profile p_s ($p_s \le np_s$) in cases where either there are several network resources available and the network operator wants to provide the maximum possible bit rate or the user profile targets at low bit rates. However, in cases where the traffic in the service area is increased, the network operator's policies can be configured to act as the upper limit or the bit rate to be achieved regardless of the users' profiles target bit rates. In these cases, it holds that $np_s \le p_s$.

5. Conclusion

This document provides insight into the processes of identification of information that can be exploited for building knowledge, information acquisition and storage, as well as in knowledge models for cognitive radio systems. As previously discussed, the information can be identified either from the user, network and environment behaviour or the decision making process. The former (user, network and environmental behaviour) relates on the process of learning and building knowledge based on the surrounding environment while the latter one (decision making process) builds knowledge based on its own behaviour introducing the aspects of self-optimization and self-awareness.

The work presented in the document has also focused on the aspects of information acquisition and storage highlighting the aspects of user, context and policy information acquisition that were already elaborated upon in ACROPOLIS Deliverable D11.1. Moreover, it has discussed the formats and structures of the stored data and its relation to the collected information that reflects the behaviour of the given network while introducing the aspect of Radio Environmental Maps as a possible data model for information storage. The design of knowledge models has also been tackled focusing on a variety of models, which have captured various aspects of the cognitive system (e.g., user/device modelling, environment modelling, network device status modelling, etc.).

The set of case studies introduced in this document will be utilized as the starting point for the remaining research work within the scope of WP11 in terms of methods and algorithms for learning and exploitation of derived knowledge as well as the algorithms for enabling collective knowledge.

6. Glossary and Definitions

Acronym	Meaning
BW	Bandwidth
CCR	Cognitive Control Radio
CoRaL	Cognitive Policy Radio Language
CPC	Cognitive Pilot Channel
CR	Cognitive Radio
CRS	Cognitive Radio System
CSMA	Carrier Sense Multiple Access
DSA	Dynamic Spectrum Access
eNB	e-NodeB
FaCT++	Fast Classification of Terminologies
GW	Gateway
HeNB	Home e-NodeB
HW	Hardware
I-Q	In-phase Quadrature
KB	Knowledge Base
LTE	Long Term Evolution
OWL	Web Ontology Language
OWL DL	Web Ontology Language Description Logics
PU	Primary User
QoE	Quality of Experience
QoS	Quality of Service
RAM	Random-Access Memory
RAT	Radio Access Technology
RDB	REM Database
RDFS	Resource Description Framework Schema
REM	Radio Environmental Map
RIF	Radio Interference Field
RMS	Root Mean Square
ROM	Read-Only Memory
RSS	Received Signal Strength
RTS/CTS	Request To Send / Clear To Send
SINR	Signal to Interference plus Noise Ratio
SSI	Simple Sequential Inhibition

SU	Secondary User
SW	Software
TCP	Transmission Control Protocol
TVWS	TV White Space
UDP	User Datagram Protocol
UI	User Interface
W3C	World Wide Web Consortium
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
XML	Extensible Markup Language

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