Distributed Resource Map: A Database-driven Network Support Architecture for Cognitive Radio Ad hoc Networks

Shah Nawaz Khan, Mohamed A. Kalil, Andreas Mitschele-Thiel
Integrated Communication Systems Group, Ilmenau University of Technology
P.O. Box 100 565, 98693 Ilmenau, Germany
Email: shah-nawaz.khan@tu-ilmenau.de

Abstract—Obtaining awareness of the operating environment is crucial to the successful operation of a Cognitive Radio (CR) network. In a multihop CR ad hoc network, aggregating knowledge about the external environment is a task which the CR nodes must perform based on their individual and collective capacity. In this paper, we introduce Distributed Resource Map (DRM), a framework for cooperation and knowledge aggregation in cognitive radio ad hoc networks. The DRM is a database-driven knowledge base aimed at exploiting distributed sensing performed by heterogeneous CR nodes and inter-nodes cooperation to maintain a network-wide support architecture. The awareness obtained through DRM architecture is used to drive the learning and decision making functions of a Cognitive Engine (CE). We present the core concepts, the architectural components, underlying knowledge aggregation functions, and a summary of the validation and realization effort. The paper concludes with a planned experimental work for DRM.

I. INTRODUCTION

Cognitive Radio (CR) [1] is widely considered and actively pursued by the industry and research community as a viable solution to the problems of spectrum scarcity and under-utilization caused by fixed, licensed allocation of radio spectrum. The realization of CR however, is a challenging task from both hardware and software points of view. For example, the design of generic radio front-ends to support runtime reconfigurations and software defined radio platforms which can code/decode signals in real-time are difficult tasks. Additionally, the network architecture also affects a CR node’s complexity by defining the desired CR functions and the architectural constraints to which the CR node must conform. For example, CR nodes operating in an infrastructure-based network can assign some of the difficult tasks in terms of hardware/software requirements to the base stations such as Primary Users (PU) localization [2] or identification of spectrum opportunities [3]. The base stations are well suited to such tasks since they can acquire a network-wide view from querying all CR nodes or obtain offline information from the network backbone. The IEEE 802.22 TV whitespace standard [4] is one example of CR networks realization effort based on a similar architecture. On the other hand, CR nodes operating in a multihop ad hoc network must perform all tasks from identifying spectrum opportunities to exploiting them for communication on their own within the general constraints of interference avoidance and maintenance of an acceptable level of Quality of Service (QoS). In such a scenario, CR nodes must rely on individual hardware/software capabilities as well as on inter-nodes cooperation to coexist with and operate without interference to other CR and legacy networks. In order to support such functions in a multihop CR ad hoc network, a network support architecture needs to be implemented. The basic purpose of having an architecture for inter-nodes cooperation is to have a level of environment awareness across the ad hoc network which can facilitate a consistent cognitive behaviour from all network nodes. The importance of environment awareness and maintenance of a network-wide support architecture for effective CR operation has been emphasized in many research articles [5][6]. It is imperative therefore, that the network support available to infrastructure-based CR nodes is similarly modelled in CR ad hoc networks where the less capable nodes can benefit from the resources of more capable peers. This paper focuses on multihop CR ad hoc network scenario where no network support architecture exists and the nodes have to self-organize and optimize their performance collectively. We present Distributed Resource Map (DRM) as a database-driven distributed knowledge-base, supported by all CR nodes of the network to develop and maintain a unique network support architecture. The DRM based network support architecture facilitates individual as well as cooperative awareness of the external environment. The scope of DRM can span from aggregating knowledge about a single resource such as RF spectrum to the realization of a distributed Radio Environment Map (REM) [5] where all possible information of use can be aggregated.

The rest of the paper is organized as follows: Section II presents the related work and reflects on some aspects of environment awareness in CR ad hoc networks which are open to research insight. Section III presents the proposed DRM in detail by specifying the sources of information for a CR ad hoc network, the architecture of a CR node intended to operate in a multihop CR ad hoc network, as well as specification of the DRM structure and the role of...
its internal components. Section IV presents some insight into the techniques/algorithms which can be applied for obtaining individual and cooperative environment awareness. The paper concludes in section V with some details of the validation and implementation effort currently being undertaken within our group and a summary of the paper in section VI.

II. RELATED WORK

A cognitive radio has to sense its operational environment in order to function within the general constraints imposed on a cognitive radio such as interference avoidance. We use “sensing” as a broad term here for all hardware and software capabilities of a CR node through which it can obtain environment awareness on its own. However, there are many limitations of individual sensing both from hardware and software points of view which limit a CR node’s environment awareness capability. Taking into consideration the shortcomings of sensing for obtaining environment awareness such as spectrum opportunity identification and interference avoidance, it only makes sense to find supportive means for such tasks in order to facilitate a cognitive behaviour. Environment awareness is a broad term used for the information aggregated by a CR node usually in the form of a structured knowledge base that can be exploited for cognitive functions including spectrum opportunity identification and exploitation. Radio Environment Map (REM) was proposed in [5] as a database-driven knowledge base containing all environment information helpful for optimizing CR functions e.g. PU localization, interference avoidance and etc. The REM concept was derived from Available Resource Map presented in [7] as a centralized database containing all radio activity information. The effectiveness of REM for cognitive functions such as learning and decision making, PU localization, and optimized spectrum sensing, etc. has subsequently been explored in literature [8] [9] [10]. The concept of REM has been applied to traditional networks as well. In [11] the authors highlight the importance of REM for frequency reuse in upcoming 4G cellular systems and claim a users’ throughput benefit of up to 14%. As part of the FARAMIR project [12], the authors in [13] present a topology engine for deriving location information from distributed measurements collected in a centralized or cluster-based REM. In [14] the authors propose to localize PU transmitters with distributed spectrum sensing performed with heterogeneous sensors. The sensors collect their measurements in a centralized database and apply localization techniques on the data to identify and locate PU transmitters residing inside the secondary users’ network.

The literature available on environment awareness through a structured knowledge base such as REM, provides sufficient fundamental proof of the effectiveness of environment awareness for enabling and optimizing CR functions. This proof however, necessitates the realization of such a knowledge base in a defined structured form. The need for a structured knowledge base is further highlighted by the limitation of a node’s individual ability to obtain environment awareness as described previously. For example, individual spectrum sensing techniques have several drawbacks related to spectrum opportunity identification and interference avoidance. Simpler spectrum sensing techniques such as energy detection are easier to implement but have a higher probability of false alarms and miss detections. Other sophisticated sensing techniques such as cyclostationary feature detection fall behind in timing, processing, and security constraints. These problems have been recognized by FCC for IEEE 802.22 TV white-space networks where spectrum sensing based approach has been discouraged in favour of a database-driven knowledge base located at the base stations.

Although the benefits of a database-driven approach are evident from the numerous works in literature, the architecture for such a knowledge base, its scope, and implementation are far away from being standardized or agreed upon. There may be different types of information in the external environment helpful for CR operation but acquisition and exploitation of such information is non trivial. For example, knowing the locations of primary users or existing network entities can contribute to avoiding creation of interference with them but obtaining such information from the environment requires allocation of certain resources from CR network. Additionally, there needs to be a framework for aggregating such information from the environment in a centralized or distributed knowledge base. The existing literature on environment awareness for CR has mainly focused on showing the benefits of environment awareness for spectrum management and interference avoidance. Negligible focus has been laid on how a network-wide integrated knowledge base such as REM, can be realized practically. The FARAMIR project [12] is one effort towards the realization of REM and definitions of its structure, API etc. However, the project is ongoing and has mainly focused on infrastructure-based scenarios. Limited attention has been given to the realization of a knowledge base for CR ad hoc networks and towards the challenges presented by ad hoc networks such as nodes’ heterogeneity, lack of infrastructural support, limited resources, and etc. The focus of this work is on multi hop CR ad hoc networks and we present the Distributed Resource Map (DRM) as a database-driven distributed knowledge base. The DRM serves as a network support architecture and develops a cooperation framework among the CR nodes. In this work we describe the basic idea of DRM, its architectural components, discussion of possible information abstraction techniques, and some insight into the realization of DRM architecture through practical implementation on a test-bed and analysis through simulations.

III. DISTRIBUTED RESOURCE MAP

The idea of DRM stems from the need for a network support architecture for CR ad hoc networks. The term “Network Support” refers to the ability of a network to relieve its nodes from performing some complex tasks on their own by providing some information from a structured knowledge base. The realization of such a knowledge base for multi hop CR ad hoc networks through a distributed database and abstraction processes is the main idea presented here. The
DRM concept drives on the fact that the collective environment awareness capacity of a heterogeneous CR ad hoc network is higher than the individual capacity of its participant nodes. In order to exploit this fact, the DRM combines the individual experiences of CR nodes into a network-wide support architecture. Complying with the concept of REM, the DRM architecture does not limit the scope of environment awareness to a particular type of resource and can be looked at as a fully distributed realization of REM for CR ad hoc networks. In the DRM based network support architecture, each CR node employs individual information abstraction techniques to develop an individual view of the outside environment from its own hardware/software resources and shares this view with other nodes to complement their acquired knowledge. The nodes can acquire and aggregate information of many types of resources e.g. from different layers of protocol stack or from different hardware components. We shall however, focus on radio spectrum resource in this paper to build on the previously described Spectrum Mapping framework [15]. Some insight into how other types of resources such as PU localization information and location based policies etc. can be mapped, is given where deemed appropriate. It is pertinent here to first consider the sources of information for a CR ad hoc network and the extent to which a network support architecture must rely on each source.

A. Information sources

Assuming heterogeneity of CR nodes in terms of hardware and software, the information acquisition capability of a network as a whole can be very diverse. Regardless of such diversity, the sources of information can be categorized into the following three main classes.

- **Individual sensing capability:** It is assumed that each CR node is capable of acquiring some level of information from the outside environment through its own hardware and software resources. However, the level and accuracy of the acquired information will differ with individual capability and location of nodes, resulting in differential views of the external environment. For example, each node can perform spectrum sensing to identify spectrum opportunities and try to avoid interference with other nodes, but different radio front-ends and sensing algorithms together with different physical locations can yield drastically different results for such tasks. A network-wide support architecture must cater for this heterogeneity by limiting the amount of uncertainty in acquired information. This could be achieved by employing intelligent abstraction techniques to the different views of CR nodes. In a CR ad hoc network, individual sensing capability of nodes is the chief source of environment awareness and facilitator of a network support architecture.

- **Communication with peers:** Considering the outlined heterogeneity of the nodes, some nodes may be more capable of information acquisition than others. In order to exploit their extra ability for the benefit of other nodes, the network support architecture must provide means of exchange of such information with other nodes. For example, one CR node may have acquired over a time a high level of information about the location of primary users in a specific area which it can share with other peers and relieve them from doing it on their own. A network support architecture must provide a framework enforcing the participant nodes to share their experiences with other peers.

- **External sources:** Some information such as location specific geographical data, information about the existing communication infrastructure, and etc. can be acquired offline e.g. from sources such as internet or other information providers. Such information may be fed into a CR ad hoc network at the time of deployment or acquired through some gateway nodes connected to the outside world. Such information can be very accurate particularly about stationary PU infrastructure or geographical/location information. However, the availability of such a source is not guaranteed and will not be addressed specifically in this paper.

B. The DRM architecture

To realize the proposed DRM based network support architecture, the structural components and their embedding inside the CR node must be defined. To do this we first present a high level view of the architecture of a CR node intended to operate in an ad hoc network; see figure 1. This architecture consists of a Software-Defined Radio (SDR) based physical and MAC layer, a Cognitive Engine(CE) for run-time adaptations, the DRM component, and an inter-component control and data message exchange framework called Signalling and Communication Link (SCL). This architecture is a composition of practically realizable components in hardware and software, specifically for nodes operating in CR ad hoc networks [16]. The embedding of MAC and Physical layer functionality into the SDR domain is critical for run-time adaptations of certain parameters such as frequency, transmission power, etc. triggered by higher level components such as a CE. The SCL is a lightweight message exchange framework for inter-process communication and is very suitable for a CR architecture.
where components can operate independently but influence each others operation through signalling and data transfer. The CE is the main decision maker regarding the physical layer parameters and relies on the run-time performance metrics of a CR node as well as on the information aggregated in DRM. For details on the implementation of these components see section V.

The DRM in the CR node architecture serves both active and passive requirements at different layers of the protocol stack by keeping recent as well as historic information in the database regarding different resources. The recent history is only based on individual sensing whereas the historical information is a combination of both individual abstraction as well as the knowledge acquired from other peers. The architecture of the proposed DRM with its main components and their interconnections is presented in Figure 2. We shall explain here the purpose of each component and its interconnections with other components with some insight into how each component operates.

- Data Acquisition Component (DAC): This component in essence is an interface to the different layers of the communication protocol stack and hardware components through which certain parameters can be observed and stored in the database (see tags (10), (11), and (12) in Figure 2). For example, DAC can capture the results of spectrum sensing performed at physical layer or acquire GPS data from the on-board GPS sensor and store these data in the database in raw format. Such raw data can later be used for developing a spectrum map based on other PU/SU activity in certain channels [15] or for identifying PU transmitters’ locations. The DAC component operates as a continuous running thread and can be controlled through DRM manager via a control link (3). The control can relate to changing the frequency of data acquisition from hardware or the types of parameters which the DAC records from different layers of the protocol stack.

- Database: The database is the main storage structure of the DRM network support architecture and stores both raw observations as well as abstracted high level information in different tables. Currently, a relational database structure is employed as it fits the requirements of radio spectrum mapping and localization data. However, a relational database structure may not be the best option when dealing with other types of information such as policy information of CE related data. Dealing with such heterogeneous requirements of storage is an open question at the moment. It should be pointed out here that each node maintains its own database independent of other nodes. The only effect of other peers on the data inside the database is through the Cooperative Abstraction Component (CAC) which is responsible for combining the external views of other nodes to the internal view in the DRM database.

- DRM Manager: The DRM Manager is the main controlling entity inside the DRM architecture and also serves as an interface for outside components to the data in the DRM database and to the abstraction algorithms used in DRM. The primary consumer of the aggregated information is the CE component in the CR node architecture which utilizes the environment information for its learning and decision making tasks and interfaces with DRM manager through data and control links (1) (2). The DRM manager has other control links with the database and the two abstraction components. User access to controlling the functionality of DRM and the data inside the DRM database can be provided through an application connected via SCL to the DRM manager.

- Individual Abstraction Component (IAC): We define abstraction as a process of deriving useful, actionable information from raw data observed through hardware/software by a CR node. The raw data could be about any particular resource type in the outside environment useful for CR optimization such as radio frequency resource. The IAC component is responsible for applying the abstraction processes on the raw data obtained by a CR node independently and for deriving high level information from it (9). Since the abstraction of radio resources is different from abstraction of location information for example, it is necessary to have individual abstraction process for each type of resource. The IAC is therefore, a plug-in based component where additional abstraction algorithms can be added as required depending on the type of resource awareness required. This extensibility is very useful in keeping the scope of DRM to certain types of information or to a complete distributed realization of REM.

- Cooperative Abstraction Component (CAC): To exploit the heterogeneity of CR nodes and to rely on the distributed network support architecture, the CAC component is responsible for querying other peers for their DRM information and sharing its own level of environment awareness with them. The CAC contains a dedicated Sharing & Acquisition sub-component (highlighted in

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**Figure 2. Overview of DRM architecture**
resource availability. Several other techniques exist in literature
state Markov chain process based on the previous observations.
whether an occupied channel will remain occupied or become
future use of channels as described in [17]. The prediction of
channel. The results of spectrum sensing can be represented
and interference avoidance. Assuming the spectrum sensing is
for performing spectrum sensing, the results can always be
awareness of hidden terminals and so the nodes/network must
in order to focus on the application of individual and coopera-
tive abstraction, we shall now take spectrum mapping which
refers to the characterization of wireless channels according
to observed activity, as a use case and explain how the DRM
framework makes it possible to create a distributed network
support architecture.

A. Individual Abstraction

To be aware of available resources and to avoid interference
with other entities in the outside environment, a CR node
has to observe radio spectrum continuously. It is generally
assumed that a CR will perform spectrum sensing regardless
of its transmission needs in order to be aware of the changes
in its environment. Regardless of the hardware/software used
for performing spectrum sensing, the results can always be
mapped to a binary sequence of 0s and 1s representing
occupied and unoccupied channels respectively or vice versa.
These binary results from spectrum sensing can be mapped
into higher level information to optimize spectrum utilization
and interference avoidance. Assuming the spectrum sensing is
accurate to an acceptable degree, the collected binary results
can be used to derive information such as prediction of
radio resource availability and appearance of PUs in a certain
channel. The results of spectrum sensing can be represented
as binary time series from which a CR node can learn about
the spectrum usage by other entities as well as predict on
future use of channels as described in [17]. The prediction of
whether an occupied channel will remain occupied or become
free in the next time frame can also be represented as a two
state Markov chain process based on the previous observations.
The authors in [18] present a prediction algorithm based on
auto-regression model for n-step-ahead prediction of radio
resource availability. Several other techniques exist in literature
[19] [20] which can serve as abstraction algorithms for radio
spectrum inside the IAC component of DRM architecture. Adaptive
spectrum sensing is another cognitive behaviour
that can be driven based on the characterization of spectrum
usage and prediction of resource availability. With adaptive
spectrum sensing a CR node can limit its spectrum sensing to
a subset of channels which are most likely to be free for a
certain time frame. However, the costs of running individual
abstraction processes all the time on a CR in terms of energy
and computation will need to be determined to get to a balance
between QoS and incurred costs.

B. Cooperative Abstraction

Individual abstraction is mainly limited to the hard-
ware/software capability of a CR node. In order to maintain
and drive a distributed network support architecture, the CR
nodes have to cooperate among themselves for the benefit
of overall network. Without a unifying network support ar-
boutch such as the proposed DRM, it is difficult to have
a cooperation among CR nodes for environment awareness.
With the CAC component of DRM running on each CR
node, a time/request driven cooperation can be implemented
facilitating collective environment awareness. However, with
the exchange of differential views of the outside environment,
the CR nodes must apply different abstraction processes than
those used within IAC component. Techniques such as fusion
of variate data [21] and voting based schemes [22] have
been shown to work for localization of transmitters and
dynamic spectrum access. For cooperative abstraction of radio
spectrum, techniques such as spectrum recommendation [23],
correlation-based statistics for differential data, and collabora-
tive filtering can be used. Apart from the costs of individual
abstraction mainly relating to energy and computation, coopera-
tive abstraction will incur additional costs of communication
which may be more expensive in a CR ad hoc network
where resource identification and utilization is difficult. At the
same time, this associated cost of communication serves as a
supportive argument for the realization of a distributed network
support architecture as opposed to a centralized approach used
in IEEE 802.22 CR standard, since communication with a
one or two hops peers is less expensive than accessing and
coordinating with a centralized entity especially in an ad hoc
network scenario.

V. Evaluation

For the realization and validation of DRM based network
support architecture, both practical implementation on a CR
test-bed and simulation analysis are pursued. In this section
we describe some details of both approaches and the platforms
and tools used for the purpose.

A. Practical implementation

We have developed the core components of DRM and other
components of the CR node presented in section III, to test
the architecture on a prototype CR ad hoc network. The CR
test-bed consists of multiple computers running Ubuntu Linux
stationed in laboratory environment. The IRIS SDR framework [24] together with USRP2 devices are used as the reconfigurable radio front-ends which support runtime reconfiguration of physical layer parameters. The required physical layer functions and medium access techniques are implemented in software using IRIS components. The reader is encouraged to look into the details of our reconfigurable MAC & physical layer and CE implementation in [25] and [16]. All components of the DRM are developed in C++ with a GUI implemented in QT windowing library. The database has been implemented in SQLite for its small footprint and embeddable nature. Energy detection based spectrum sensing component is implemented in SDR which senses the power levels on different frequency channels and produces results in binary (1 for free and 0 for occupied channels). Currently, the spectrum sensing is only limited to 2.4GHz ISM band. The results of spectrum sensing are stored with timestamps in a table inside the DRM database. Currently, only the IAC runs on the raw data to derive high level information characterizing the channels according to the observed activity. The information in DRM is used for channel selection and handover operations. When an application needs to send data or the node has to perform a spectrum handover for ongoing communication, the CE is notified which queries the DRM for the best candidate channels according to the aggregated information. The DRM responds by providing the specification of the best channels i.e. frequency, bandwidth, and some parameters needed by USRP2 hardware to tune to the recommended channel. The CE submits the necessary reconfiguration commands to the SDR which reconfigures the physical layer. The user can interact and observe the behaviour of the system with a GUI component which also provides some control such as changing specifications of channels or stopping the abstraction process in DRM. The Signalling and Communication Link (SCL) developed from ZeroMQ and Google’s protobuf libraries, provides a convenient way of control and data exchange among the main components of the CR architecture.

B. Simulation analysis

The practical implementation effort described in previous sub-section is limited on many fronts which makes validation and use of DRM very difficult. For example, CR nodes located in a laboratory environment inside a building tend to observe the same environment and produce more or less the same results which makes the CAC less useful since all nodes have the same view acquired on their own. To cater for this and other shortcomings of practical testing, a simulation platform is being developed to integrate all the implemented components in a multihop CR ad hoc network. Our simulation platform is based on OMNeT++ which is a discrete event simulation system together with MiXiM model for OMNeT++ which provides some physical layer details and protocols [26]. Since this platform does not provide direct CR simulation support, we are focusing on extending it to simulate the proposed CR node architecture along with a realistic wireless environment. The DRM components developed for practical test-bed can be directly imported into the simulations with very little modifications. The main effort in modifying the simulation platform is in extending the physical layer representation and modelling in MiXiM framework to make it suitable for cognitive dynamic spectrum access simulations. We shall report on the results of our experiments from both practical implementation and simulation analysis in near future as the work is still in progress. The initial outcomes from the implementation of the different components look promising as the proposed architecture for CR node works as expected.

VI. SUMMARY & FUTURE WORK

In this paper we presented a novel distributed network support architecture for CR ad hoc networks called distributed resource map. We highlighted the importance of having such an architecture for exhibiting a cognitive behaviour across the network and the existence of limited work on the realization of such an architecture for CR ad hoc networks. The DRM based network support architecture makes it possible for CR nodes to drive a network support architecture and complement each others’ awareness while deriving information on their own. The extendible architecture of DRM makes it very suitable to test different types of resource awareness techniques by plugging in new abstraction algorithms and acquiring the needed raw data from DAC. In future we intend to validate the positives of DRM with the outlined experiments in previous section and share the results with research community. Also an insight into different abstraction techniques and their performance within the DRM architecture will be investigated in the near future.

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