Neighbour and network discovery in cognitive radio networks: research activities and results in the ACROPOLIS Network of Excellence

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***Abstract*—Cognitive radio networks operation relies on the capability to gather information about the surrounding environment, as regards both internal network status (presence and capabilities of other devices belonging to the same network) and external systems potentially coexisting with the cognitive network. In particular, retrieving information at the local level is a function required to all wireless networks, and goes under the name of *neighbour discovery.* Under this aspect, cognitive networks make no exception. Similarly, cognitive networks share with traditional wireless networks the necessity of a function for retrieving and exchanging information on a network wide scale, referred to in the following as *network discovery.* The definition of efficient neighbour and network discovery strategies for cognitive networks, taking into account their specific characteristics, is one of the goals of the research activities undergoing within the framework of the ACROPOLIS NoE. In this work, neighbour and network discovery solutions currently under investigation within the ACROPOLIS joint research activities are presented, and future research lines are identified. The paper first presents algorithms and results on neighbour discovery and Medium Access Control, and moves then to network wide protocols by presenting the work carried out in ACROPOLIS on routing for underlay cognitive networks. The paper provides then an overview on the common simulation platform developed within ACROPOLIS to investigate neighbour and network discovery, and finally discusses future research directions on such topics.**

***Index Terms*—Cognitive radio, neighbour discovery, network discovery**

I. INTRODUCTION

The efficient operation of cognitive radio networks requires to each device the capability to gather information about the surrounding environment, as regards both internal network status (presence and capabilities of other devices belonging to the same network) and external systems potentially coexisting with the cognitive network.

In particular, retrieving information at the local level is a function required to all wireless networks, and goes under the name of neighbour discovery. Under this aspect, cognitive networks make no exception: these networks pose however specific challenges when it comes to establish a communication channel between neighbouring devices, due to the impact of the coexistence with other radio systems.

Similarly, cognitive networks share with traditional wireless networks the necessity of a function for retrieving and exchanging information on a network-wide scale, referred to in the following as network discovery. In this case as well, however, the specific characteristics of cognitive networks make the deployment of efficient network discovery strategies an even more challenging task.

The definition of efficient neighbour and network discovery strategies for cognitive networks is indeed one of the goals of the research activities undergoing within the framework of the Work Package 10 of the ACROPOLIS NoE, along with the definition of efficient inter-network communication and coordination solutions.

In this context, the present document addresses the issues of neighbour and network discovery in cognitive wireless networks by presenting the solutions currently under investigation within the ACROPOLIS joint research activities.

The paper is organized as follows. Section II first presents the analysis carried out within ACROPOLIS on the performance of neighbour discovery schemes in cognitive networks, taking into account the impact of imperfect sensing in network devices carrying out the discovery procedure, and introduces a novel neighbour discovery scheme combined with a Medium Access Control scheme specifically tailored for a Cognitive Network. Section III moves to the problem of network discovery, focusing on the research activity on routing for underlay networks carried out in ACROPOLIS. Next, Section IV presents the advancements achieved in ACROPOLIS for the simulation of a cognitive radio network in the OMNeT++ simulation environment, in terms of channel modeling as well as packet error rate evaluation. Finally, Section V concludes the paper and identifies future research directions.

II. Neighbour discovery and MAC

Neighbour Discovery (ND) represents a crucial aspect of mobile ad-hoc (i.e. self-organizing) networks and, lately, cellular networks due to the development and deployment of unsupervised picocells and femtocells. The goal of the ND process is to discover and identify the nodes' network neighbours (or *peers*) based on their Network interface ID (NID), GPS location etc. Therefore, neighbour discovery plays an important part in the optimization of the communication features of the network.

Neighbour discovery can be broadly defined as the process of acquiring information about the local environment including, among others, the following aspects:

- Presence of other devices
- Capabilities of other devices
- Information available at other devices

Neighbour discovery represents a setup and operation procedure within wireless networks that forms the basis for the following network procedures:

- Network association
- Network organization (e.g. clustering)
- Support for end-to-end algorithms and protocols (e.g. routing in multi-hop networks)

A key requirement in the achievement of neighbour discovery is the agreement on a common channel on which the information exchange between network terminals can take place. Defining such common channel is an integral part of the neighbour procedure, and depending on the characteristics of the network under consideration, this task can prove quite difficult to complete.

Single channel networks, i.e. networks of devices that are using only one channel, are the easiest ones to address, as a common channel is in this case automatically defined and available. In this context, neighbour discovery has to deal mainly with the synchronization between terminals, in order to enable the information exchange. Neighbour discovery requires additional efforts if the common channel is not defined a-priori, and varies thus in time and/or space. Classes of networks that are characterized by this behaviour include for example networks of devices with directional antennas and multiple channel networks, in which multiple channels are available, and a common channel is selected as a function of internal network operation. The above networks pose an additional problem during neighbour discovery. First, a common channel must be identified between those available to network terminals, and next the synchronization phase (as described above for the single channel networks case) must take place.

There have been several proposals in the literature to perform neighbour discovery in multi-channel networks [1][2][3][4]. The issue of common channel selection is typically addressed in either of two ways: random channel selection, straightforward but unable to guarantee a bounded neighbour discovery time, vs. specific sequence design, guaranteeing a bounded discovery time at the price of a loss of generality.

Cognitive networks can be seen as multiple channel networks, but pose additional challenges related to the coexistence with other radio systems:

- The available radio resource (i.e. available channels) varies over time as a result of the activity of other radio systems;
- The available radio resource can be different for different terminals in the same network due to different geographic positions influencing the sensing results.

In this context, the ACROPOLIS research activity focused on the analysis of the performance of random discovery schemes in presence of imperfect sensing information. Figure 1 presents an example of the results obtained during this analysis, showing the impact of the probability of false alarm and of the number of channels to be considered in the neighbour discovery process between two cognitive devices. A detailed description of the analysis and of the results can be found in [5], while an extension of the work, with the application to the problem of optimal network selection for a mobile cognitive device, was proposed in [6], [7].

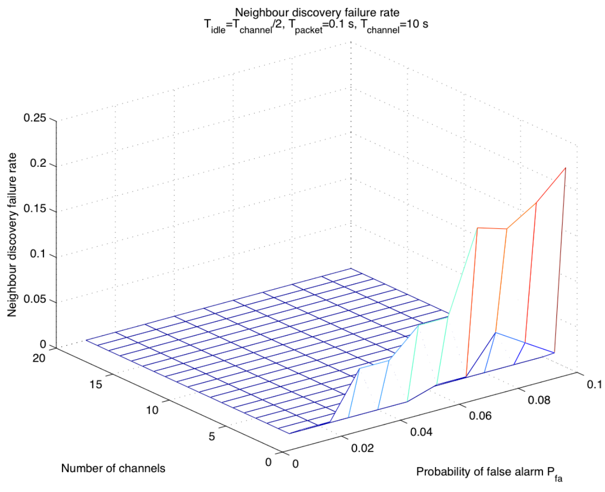

Fig. 1. Neighbour discovery failure rate as a function of probability of false alarm and number of channels, drawn from [5].

Research on neighbour discovery in ACROPOLIS also addressed the problem of specific sequence design capable of addressing the problem of neighbour discovery in a network of devices with asymmetric channel sets, in conjunction with MAC design. Moving from previous work carried out by

ACROPOLIS partners and focusing on neighbour discovery in asymmetric channel scenarios [8], [9] and MAC design [10], a novel rendezvous scheme addressing both neighbour discovery and medium access was proposed in [11], [7]. The proposed protocol combines the effective selection of channel hopping sequence provided by the gQ-RDV neighbour discovery protocol defined in [8], [9] with the efficient rendezvous algorithm defined in the RAC^2E MAC protocol [10], in order to obtain shorter neighbour discovery times. The resulting RAC^2E-gQS protocol, compared to other solutions previously proposed in the literature, shows indeed lower medium times required to achieve discovery and a higher number of potential windows where nodes share the same channel and can thus complete discovery. Details on the proposed protocol and on performance evaluation results can be found in [11], [7].

III. Network discovery

The research activity within ACROPOLIS on network discovery focused in particular on routing. The problem of routing in cognitive networks encompasses both the case of interweave networks that use spectrum holes and dynamic channel selection for creating end-to-end paths and of underlay networks that optimize their route selection process by taking into account the coexistence requirements determined by the presence of other networks.

Recently, the research community focused on the impact of channel switching on routing performance, considering in most cases the latter case defined above, typical of a Dynamic Spectrum Access (DSA) network.

In [12], [13] the authors propose a routing metric that models the end-to-end delay by taking into account both the average delay introduced by collisions on a single frequency band and the delay introduced by each channel switch required along the path.

The work presented in [14] addresses the same problem by proposing a solution for spreading the information on the positions of the nodes and the channels available to each node, in order to enable efficient routing. The proposed information exchange protocol, based on a broadcast packet exchange, is however only tested in a very favourable scenario, characterized by an error-free channel and collision-free medium access.

An additional characteristic of cognitive radio networks that may impact routing is the fact that the network can be formed by devices complying to different wireless standards. Furthermore, a network node can potentially support more than one wireless network interface. The routing protocol proposed in [15] deals with this aspect, by introducing a routing metric that models the different characteristics of each radio link available between network nodes. The metric is used to build a routing tree between a base station and wireless nodes in the network.

As already mentioned, dynamic channel selection is only one of the possible solutions to allow coexistence between cognitive secondary users and primary users. Underlay systems such as Ultra Wide Band (UWB) offer an alternative solution. In the case of UWB, thanks to the huge bandwidth and the low power levels allowed by regulation, an UWB signal is in most cases invisible to the primary user. The main problem in routing within an UWB network is thus to cope with the interference caused by primary users. This goal can be achieved by including the interference generated by such users among the routing criteria. A cognitive routing model addressing this problem was proposed in [16], [17]. The approach proposed in [16], [17] moved from the identification of key factors relevant to the selection of a multi-hop route, that can be listed as follows: synchronization, power, Multi-User Interference (MUI), link reliability, traffic load, end-to-end delay, battery autonomy, coexistence requirements. Correspondingly in a routing cost function was proposed that took into account each of the above factors with a dedicated term. The coexistence term, in particular, aimed at taking into account the reciprocal impact of the underlay UWB system and a coexisting primary system. Results in [16], [17] highlight how including coexistence-related information in the routing process can significantly increase network performance and energy efficiency, by allowing to avoid routes prone to interference generated by high power primary systems.

Research on routing in ACROPOLIS focused indeed on the case of UWB underlay networks, taking however into account a recent evolution in the field of cognitive radio, related to the introduction of external databases capable of providing information about the presence, activity and physical position of primary transmitters, to be accessed by secondary cognitive devices in order to determine spectrum availability by building what is currently referred to as a Radio Environment Map, based on their own position.

Although the approach was mainly proposed to regulate and enable opportunistic use of TV band white spaces, the idea of taking advantage of knowledge of position information about the primary users to optimize cognitive radio network operations and in particular route selection is appealing beyond the specific "white spaces" application scenario.

In the last few years the growing availability of GPS-enabled devices caused an increasing interest in the wireless networks research community for routing protocols capable to exploit the localization information in the path search procedures. A position-based routing protocol, possibly combined with a coexistence aware routing cost function as the one discussed above, could increase the performance of a cognitive network by reducing the mutual impact of coexisting network: a joint research activity in this direction was started within ACROPOLIS, aiming at a solution that a) takes advantage of position information in order to adapt the antenna pattern, so to maximize emissions in preferred directions, and b) operates in absence of dedicated hardware for positioning, or when the required infrastructure is not accessible (e.g. indoor operation).

The solution proposed in ACROPOLIS towards the achievement of the above goals is to equip each cognitive device with an array of antenna elements, capable of dynamically steering the antenna beam by means of beamforming, while providing a way of collecting position information by means of cooperation between devices implementing a Direction of Arrival (DOA) positioning technique, based for example on the well known MUSIC algorithm [18].

The solution takes advantage of the array of antenna elements not only to determine the direction of arrival of signals, but also to avoid emitting towards specific directions, by adopting a technique known as beamforming; the coexistence capabilities of a secondary network can be significantly improved by imposing nulls on directions leading to the positions occupied by primary systems. The beamforming technique used in this work is more commonly referred to as Orthogonal Transmit BeamForming (OTBF), where the transmitted signals are made orthogonal to each other, so that co-channel interference is completely suppressed, without any further processing at the receiver end. The main goal of the beamforming technique is satisfy the signal-to-interference-plus-noise ratios (SINR) of the secondary users while keeping the interference to the primary users below a certain threshold. The direction of the beam pattern is determined by utilizing the DOA information. More details can be found in [19].

The routing solution was developed in two steps:

1. In a first iteration, beamforming was applied hop by hop to predetermined paths resulting from the operation of a location-based routing protocol; two such protocols were considered, namely Location Aided Routing (LAR) [20] and Greedy Perimeter Stateless Routing (GPSR) [21]. Simulation results showed that the introduction of beamforming allowed to increase throughput in the secondary network, provided that the position information used to determine the end-to-end path and to steer the antenna beam was accurate enough [22], [5].
2. At a latter stage, the beamforming was taken into account in the selection of the path, by allowing local modifications of the path determined by the location-based routing on the basis of the expected performance of the physical layer. The choice of only permitting local modifications allowed to keep the routing algorithm decoupled from the beamforming physical layer. The performance analysis highlighted in this case as well a performance improvement, in particular in cases where coexistence requirements were particularly strict due to the presence of multiple primary receivers in the area interested by cognitive network operations [23], [7].

Further developments to the ACROPOLIS routing solutions will be discussed in Section V.

IV. Simulation Platform for Neighbour and Network Discovery

Accurate performance evaluation of the MAC and network algorithms and protocols proposed within ACROPOLIS required the development of a reliable simulation platform capable of reliably and accurately modelling all the relevant aspects in the operation of a cognitive radio network, from channel modelling to interference calculation and Packet Error Rate, from terminal mobility to primary systems activity model; OMNeT++ [24] was selected as the simulation environment. The first step in the development of the simulation platform was the introduction of an abstraction network model. The reference abstraction scenario defined as a result of this effort is shown in Fig. 2. a detailed description of all the modules and functions proposed in the model can be found in [5]. Such modules and functions were defined taking into account inputs from all ACROPOLIS partners, so to include all key entities and roles required for describing the set of scenarios considered in the ACROPOLIS project. An example of the mapping of the abstraction scenario on a specific application scenario, that is a reconfigurable UAVs network, is presented in Fig. 3.

The abstraction scenario was then translated in a generic cognitive terminal architecture that was in turn implemented in the OMNeT++ simulation environment. The architecture of the cognitive terminal as implemented in OMNeT++ is presented in Fig. 4.

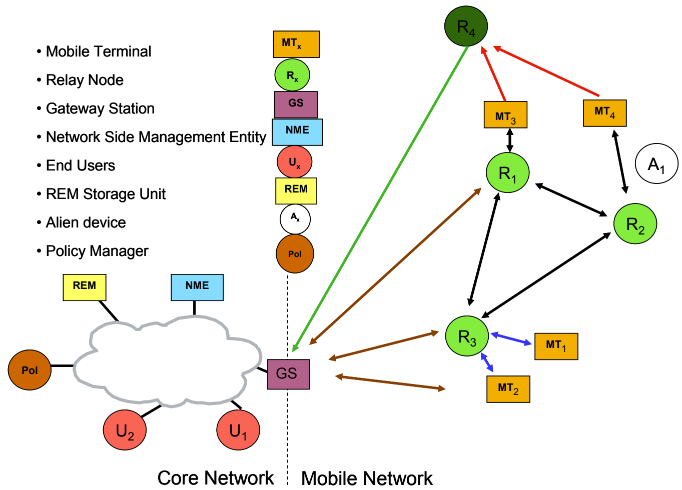

Fig. 2. Reference abstraction scenario, drawn from [5].

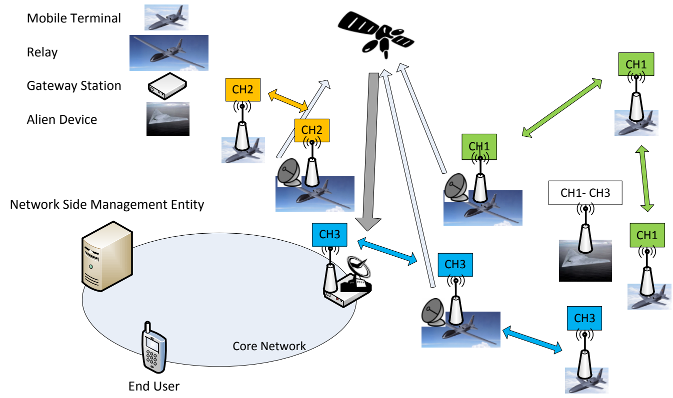

Fig. 3. Mapping of the abstraction scenario on a reconfigurable UAVs network scenario.

In addition to the definition of a new architecture, the development of the simulation platform led to advancements

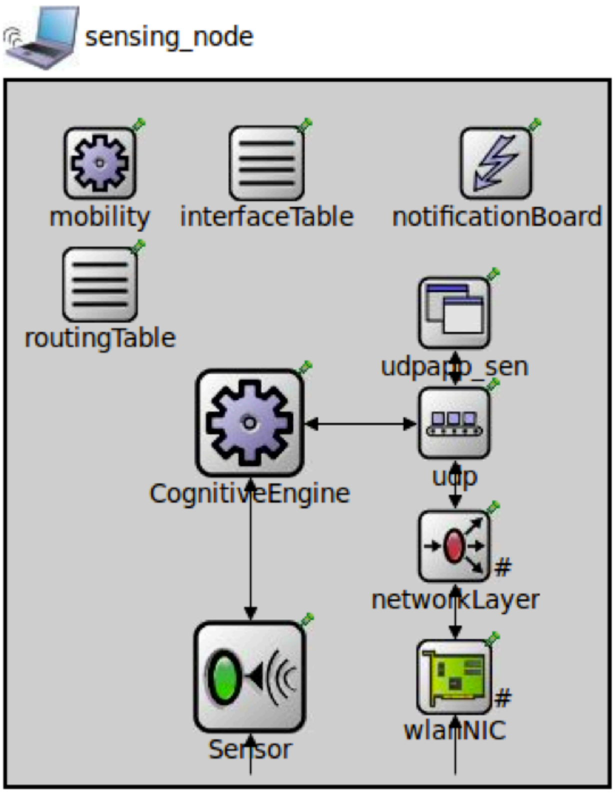

Fig. 4. Architecture of a cognitive terminal as implemented in the ACROPOLIS simulation platform for neighbour and network discovery performance analysis.

and improvements compared to models previously available in OMNeT++ under several aspects listed below.

- Channel modelling and spatial correlation – an advanced model for spatial correlation of fading was introduced in the channel module, so to allow for the evaluation of cooperative spectrum sensing schemes and sensing aware network organization solutions. Further details can be found in [25].
- Mobility models – advanced mobility models were implemented in order to test mobility-aware clustering solutions, considering both uncorrelated and correlated mobility patterns between different terminals.
- Evaluation of Packet Error Rate as a function of packet collisions and corresponding interference – real-time tracking of packet collisions with resolution equal to the symbol time was introduced in the physical layer model of the OMNeT++, allowing the definition of groups of symbols (bits in the following, assuming a binary modulation) subject to the same interference level, referred to as Bit Regions [23]. For each Bit Region the simulator evaluates an average Bit Error Probability, determines the number of bit errors, and then applies the selected coding scheme in order to determine whether the errors are recoverable or not. An example of the Bit regions defined by the interference tracking code is shown in Fig. 5.
- Introduction of new MAC, sensing and routing protocols – Several new routing protocols were implemented, including the LAR and GPSR protocols. In addition both centralized and distributed cooperative spectrum sensing schemes were implemented, including different sensing data fusion strategies (OR, AND, majority).

V. Conclusions

This work presented and reviewed the research activities carried out within the ACROPOLIS NoE on the topics of neighbour and network discovery. Collaborations between ACROPOLIS partners led to the definition of novel solutions for neighbour discovery, MAC and routing in cognitive networks. In addition, the need for a simulation platform for the performance evaluation of the proposed solution led to the development of an advanced platform based on OMNeT++ for the simulation of cognitive radio networks.

Future research directions include the extension of neighbour discovery solutions, exploring approaches based on beacons or other forms of cooperation between primary and secondary systems. In the case of routing, the work will be completed by defining a routing metric that includes the expected interference taking into account the impact of beamforming, so to determine in a single step the optimal path in a network of cognitive terminals equipped with arrays of antennas.

Finally, the activity on the simulation platform will proceed by completing the integration of the different new OMNeT++ modules developed within ACROPOLIS, since some of the improvements were carried out in parallel in order to enable timely performance evaluation of the different proposed solutions.

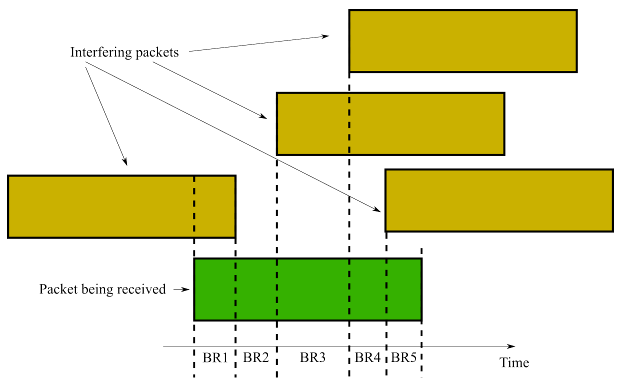

Fig. 5. Example of bit region identification during a packet reception in OMNeT++; 5 Bit Regions (BR1 to BR5) are identified based on the arrival times of interfering packets.

Acknowledgment

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