Sensor Networks for Cognitive Radio: Theory and System Design

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Abstract: Following current trends towards dynamic spectrum allocation and cognitive radio, this paper proposes a new approach and innovative techniques to support the coexistence of licensed and unlicensed wireless users in a same area. The proposed concept, called Sensor Network aided Cognitive Radio, consists of a wireless sensor network able to assist the cognitive network by providing information on the current spectrum occupancy. This concept, that will address various operational scenarios in the future networks, involves a set of advanced wireless communications techniques like spectrum sensing, interference management, cognitive radio reconfiguration management, cooperative communications, end-to-end protocol design and cross-layer optimisation. All these enabling techniques together will form a compound system able to improve the spectrum use in a significant way. The main target scenario we consider is the use of nomadic cognitive radios in urban and suburban areas. Our objective is to develop a proof-of-concept – scheduled in 2010 – of the Sensor Network aided Cognitive Radio technology by implementing such techniques and integrating them on a hardware radio platform, which will allow us to assess the efficiency of the technology in a realistic environment.

Keywords: Cognitive Radio, Dynamic Spectrum Allocation, Sensor Networks.

1. Introduction

Cognitive radio is an emerging wireless communications concept in which a network or a wireless node is able to sense its environment, and especially spectrum holes, and change its transmission and reception chains to communicate in an opportunistic manner, without interfering with licensed users. Cognitive radio thus aims to improve the way the scarce radio spectrum is utilized [1][2]. Indeed today's approach is based on dividing the spectrum into small pieces, each for a specific purpose. Since the applications use their spectrum to a limited extent, this leads to the unwanted situation of under-utilization of this scarce radio resource. While radio communications grow constantly, regulation authorities recognise that the current approach is reaching its limits and are planning to open some bands for cognitive use. Consequently, cognitive radio and dynamic spectrum allocation are becoming key technologies and key research activities in the field of wireless communications. Our objective is to propose a system solution that maximizes the capacity of the unlicensed cognitive network while ensuring that it does not cause harmful interferences to the licensed network.

The capability to reliably detect spectrum holes in order to avoid interference with the licensed network currently in use is the actual major difficulty faced by the cognitive radio, all the more as a fine granularity of spectrum allocation (time and frequency) is targeted. We suggest a system approach to address this challenge of the introduction of the cognitive radio in the future networks. An innovative concept is proposed: the *Sensor Network aided Cognitive Radio* technology, that utilizes sensor networks to support the coexistence of licensed and unlicensed wireless users in a same area. The general scenario of the Sensor Network aided Cognitive Radio is depicted on Figure 1. In the system we intend to develop - in the framework of SENDORA FP7 ICT project, the network of cognitive users, called the secondary network first communicates with the wireless sensor network. The wireless sensor network scans the spectrum usage, and is thus aware of the holes that are currently available and can potentially be exploited by the secondary network. This information is provided back to the secondary network. The secondary users are now able to communicate without causing harmful interferences to the licensed network, called the primary network.

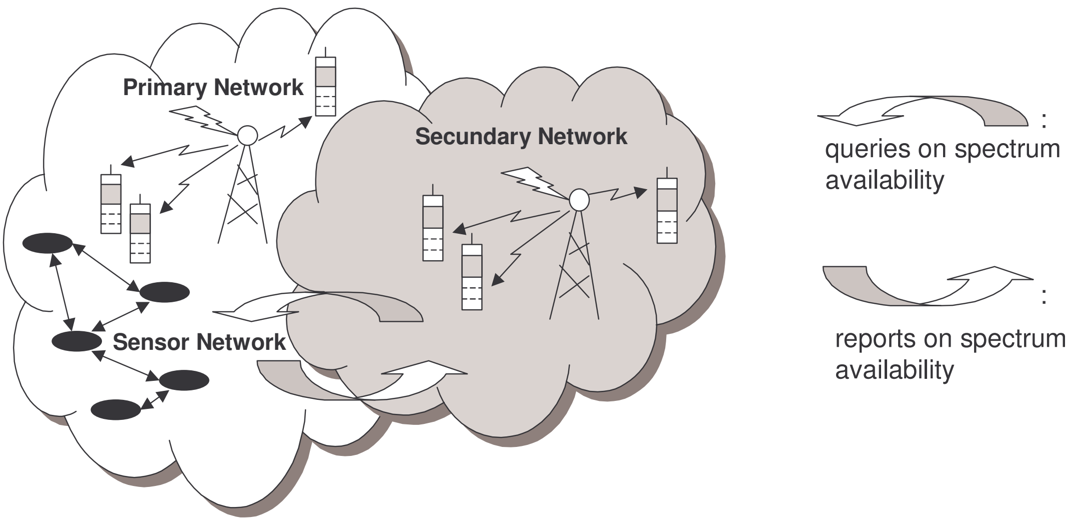

Figure 1: Sensor Network aided Cognitive Radio general scenario

The proposed approach allows to solve the issue of the reliable detection of spectrum holes, thanks to the introduction of the sensor networks and associated networking capabilities in the system. Beyond the limited current state-of-the-art on cognitive radio, this technology will allow to address a very dynamic and competitive mixed radio access between cellular and broadband technologies.

This paper will not only discuss the various different advanced techniques enabling the Sensor Network aided Cognitive Radio technology, but will also propose an analysis of the potential exploitation of these techniques. After studying the challenges raised by cognitive radio, this paper specifies the scenarios targeted by the Sensor Network aided Cognitive Radio, and especially the potential operational use of this technology. Then, the enabling techniques are detailed, in particular the spectrum sensing, the sensor network dimensioning and the cognitive actuation of secondary network radios, as well as collaborative communications and end-to-end communications between sensors. Finally the integration of these techniques and the assessment of the proposed technology are addressed.

2. Sensor Network aided Cognitive Radio innovative concept

2.1 – Need for an optimised use of the spectrum

The basic idea of cognitive radio concept is that an unlicensed (secondary) user can be permitted to use licensed spectrum, provided that it does not interfere with any primary users. The research challenges include devising methods for how such co-existence can be implemented in practice. The motivation for cognitive radio stems from various measurements of spectrum utilization, which generally show that spectrum is under-utilised, in the sense that the typical duty cycle of spectrum usage at a fixed frequency and at a random geographical location is low. This means that there are many holes in the radio spectrum that could be exploited [3]. While this observation stands in some contrast to the general picture of spectrum allocation that one can infer from a frequency allocation chart, the presence of spectrum holes is understandable given how inefficiently radio resources, and spectrum in particular, are in fact utilized in current systems. Cognitive radios should be able to exploit these spectrum holes by detecting them and using them in an opportunistic manner. In particular, it has been argued that cognitive radios could be permitted to transmit if they cannot "hear" any primary transmission [4].

The difficulty associated with the opportunistic exploitation of spectrum holes is illustrated in Figure 2.

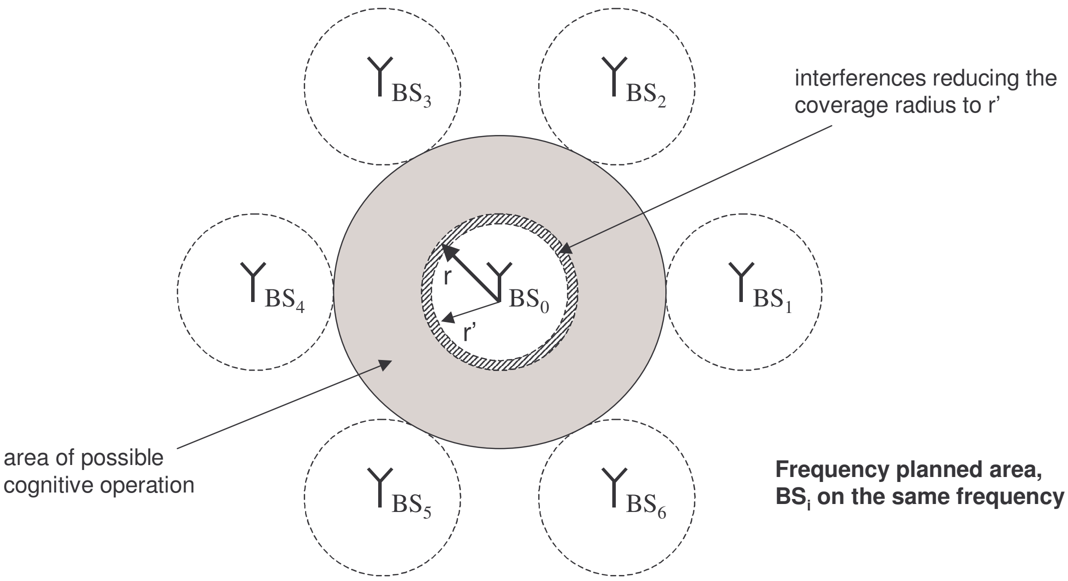

Figure 2: Area of potential cognitive operation

This figure shows a frequency planned network with a base station BS_0 that serves users in a primary cell of radius *r*, and the first tier of interfering base stations $BS_{1\text{-}6}$ that use the same carrier frequency. Between the coverage area of BS_0 and those of BS_{1-6}, there is a circular ring within which no primary users can communicate with BS_{0-6}, owing to the low signal-to-(noise-and-interference) ratio they would experience. (Primary users in this ring are served by other primary base stations using other frequencies, not shown in Figure 2). A spectrum measurement in the circular ring would then likely show that there are spectrum holes, and thus that cognitive radio devices – using very small transmit power – could exist in this area of possible cognitive operation [5]. The difficulty with this is that such cognitive operation will inevitably create interference (no matter how little) that will reduce the coverage radius of BS_0 from r to r'. This is true also for cognitive devices that try to infer the duty-cycle of the primary network and exploit temporal spectrum holes. For the impairment experienced by the primary system to be as small as possible, a cognitive device must be able to detect very reliably whether it is far enough away from a primary base station and/or whether this primary base station is silent at a given point in time. For an individual detector this is very difficult due to different radio propagation paths and it may need to sense primary user signals buried deep under the noise floor. It has therefore been argued in the literature that cooperation among sensors is imperative. In fact some authors, see e.g. [6], claim that spectrum sensing for cognitive radio is impossible without cooperation. Indeed cooperation allows the mitigation of shadowing and fading effects as well as the use of simpler individual detectors without compromising the performance. As predicted by [7], gains in the order of 40% to 100% can be expected, in terms of spectral efficiency per user, based on coordinated opportunistic spectrum sharing using cognitive radios, compared to uncoordinated competition. Cooperative sensing is consequently a cornerstone in the Sensor Network aided Cognitive Radio technology we will develop.

2.2 – Beyond state-of-the-art concept

While cognitive radio is a hot topic of current research, most efforts address only parts of the challenge of utilising unused spectrum with cognitive radios [6-14]. The approach we propose will address the significant questions related to cognitive radio systems in a common framework, ensuring this way that the results achieved in the different parts of our project can be integrated and can provide a functioning system.

The project will derive novel theoretical tools based on the combination of different disciplines, such as teletraffic theory, statistical signal processing, information theory, game theory and optimisation. These tools will help us understanding the capabilities and the limitations of the proposed complex communication system. Considering the theoretical results, we will then provide a system definition and a cognitive radio testbed proving the feasibility of the proposed concept.

2.3 – Scenarios and potential exploitation

Beyond the technical challenges to enable efficient communications while minimizing interferences to primary users, the capabilities provided by the Sensor Network aided Cognitive Radio technology will allow to address various scenarios of use and therefore new business cases. It should allow the telecommunication operators to improve the utilization of their spectrum resources. The defined system may be used to introduce new services in their networks but also to offer telecommunication services in markets where they do not own spectrum.

The scenarios will lead the design of the technology: the geographical layout of the sensor network, the radio propagation environment, the amount of available spectrum, the power available for the inter-node transmissions and the required sensitivity of the sensor network are parameters that strongly depend on the targeted scenario. Therefore the scenarios will provide requirements in one hand, but the design of the overall system will also show operational limits on the other hand. Thus, an optimised system shall be reached by combining theoretical studies and practical implementation.

The target generic architecture (Figure 1) can be derived into several architectures, depending on the way the sensed information is transmitted and the way the computation of the decision (and the way it is transmitted) is performed. Distributed, centralized and hybrid architectures are foreseen. Moreover, the cognitive network may be cellular-oriented or ad hoc-oriented. This leads to different application scenarios.

A first class of scenarios makes use of dedicated wireless sensor networks deployed by an operator to offer for example low cost services. The sensor network continuously monitors the spectrum and identifies unused frequencies. The users' terminals communicate with the sensor network to get information/instructions on which frequency/time slots to use. The operator might be the owner of the primary technology spectrum license, or it can be owned by an independent cognitive radio operator specialized in providing these kinds of services. Use cases of this scenario class can be foreseen in a urban or suburban area. The cognitive radio users, which are passing through the area, may have handheld terminals or laptops that query the sensor network or a special station connected to the sensor network. The services that will be provided over the cognitive radio system may typically be internet access and low to medium grade voice services. The cognitive radio network may support nomadic and portable usage, and perhaps even simple mobile usage. This kind of use is expected to have a very good commercial potential since the number of users can be large, provided that the system is able to give sufficient capacity.

In a second class of scenarios, ad hoc radios are both secondary user terminals and sensors (e.g. integrated into smart phones or laptops). These radios have to discover each other, build an ad hoc network, cooperate to perform distributed sensing – achieving the required detector performance level to be able to use the spectrum without disturbing the primary users – and transmit their own communications in an already licensed area. Such a sensor network can also be used only for its spectrum monitoring capability to assist a separate secondary network.

Promising target scenario for the Sensor Network aided Cognitive Radio technology is the nomadic broadband in urban and suburban areas. In this scenario cognitive radio is used to provide a broadband service to users that are stationary when logged on the network. This scenario is expected to have a very good market potential since it can provide many of the same services as mobile broadband at a lower cost. Cognitive radio is also seen as the best solution for this application, since the system can use the frequency that best fit the radio propagation environment each user experiences. Alternative licensed technologies have to operate in given narrow frequency bands and can not adapt to the propagation environment in the same way. The capacity of cognitive radio will also be better since the frequency resources available will be larger. For such a scenario, a hybrid spectrum sensing architecture is foreseen.

Additionally to the potential scenarios of exploitation of the Sensor Network aided Cognitive Radio technology, the expected results may influence standardization and spectrum allocation, both in terms of policy and granularity.

3. Enabling techniques for Sensor Network aided Cognitive Radio

When defining the Sensor Network aided Cognitive Radio system we have to address the following challenges:

- *Efficient spectrum monitoring*, that is, design of new robust local spectrum sensing algorithms, whose detection power will be enhanced by processing data from several sensing devices in order to perform distributed detection of primary users. This task requires the analysis of the primary signal properties under different primary network technologies, including its dynamic behaviour and possible cyclostationarity. Spectrum sensing should be able to distinguish between the primary user signals and other interfering signals. The spectrum monitoring techniques proposed will take into account the possible limitations of the sensor hardware in RF and digital domains as well as the cognitive actuation process such that the distributed sensing can provide the information required for cognitive actuation on time. Design of a smart sensing policy for a distributed sensor system allows for employing simpler detectors, as well as reducing power consumption and overhead in sharing the sensing results.

- Improved understanding of the *cognitive radio control actuation loop* by providing answers to the following questions: a) how much side spectrum information is really needed for an efficient co-existence between primary users and secondary users, b) what are the most efficient actuation rules that have to be taken by the secondary users once they have this spectrum related information, and c) should sensing abilities be better implemented in the secondary user terminals, or is it preferable to deploy a dedicated sensor network in charge of spectrum sensing ? None of these questions have been answered today. Based on the findings on cognitive actuation, we can define the requirements on the granularity and accuracy of spectrum sensing provided by the sensor networks and performance requirements in terms of sensor networks throughput and data fusion delay.

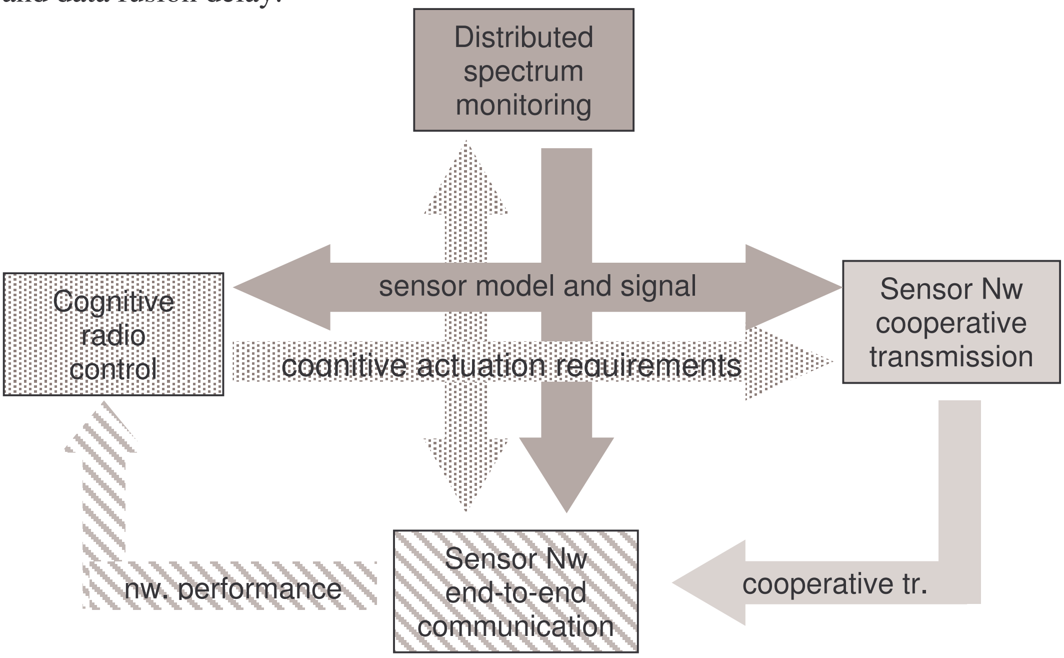

Figure 3: Dependencies between design challenges in the Sensor Network aided Cognitive Radio System

- Considering the sensor network, novel physical layer *cooperative transmission* techniques will be designed, by modifying suitably various approaches (Virtual Beamforming, Amplify & Forward, Decode & Forward, Compress & Forward). Since sensor networks are typically power limited, we will invent power allocation strategies that optimally make use of the available radio resources. In particular the devised transmission mechanisms will consider the specific correlation structure of spectrum measurement data.
- The design and evaluation of a complete *cross-layer optimised protocol stack* for end-to-end query dissemination and data gathering in the wireless sensor network shall also be addressed. The protocols design will be driven by the unique needs of the considered application scenarios in terms of sensing coverage, measurements reliability and accuracy, latency and energy constraints. We will develop models for network dimensioning, taking into account the foreseen limitations of the sensing node

hardware. Protocols and algorithms for data gathering will then be designed and evaluated. The proposed solutions will be integrated and a cross-layer optimised protocol stack will be designed specifically for the spectrum monitoring application.

Figure 3 shows some of the dependencies between the addressed challenges. Our aim is to monitor these dependencies constantly providing a consistent system design in this way.

4. System integration and proof-of-concept

Two phases are required to assess the Sensor Network aided Cognitive Radio concept. First, as this technology shall be considered as a global system, the functional integration and simulation based analysis of the enabling techniques detailed above are necessary to achieve and measure potential results in terms of spectrum use efficiency.

Then, the technology shall be demonstrated in a realistic environment with a primary network in use to face real conditions and thus prove the concept. For that purpose a radio demonstrator will be developed, in particular by integrating the algorithms defined in the study. Two hardware platforms will be designed:

- One platform dedicated to digital signal processing, composed of high capacity FPGA components. The design of the digital baseband processing of such an extremely agile system is a very challenging task. The required processing power is huge in most of the functional unit and the memory needs and memory bandwidths are also usually very high. But the two most challenging aspects may be the partitioning of the system in hardware and software processing units, and the system integration including the design of embedded software.
- One RF platform with frequency agility and two antennas allowing communications through two separate channels. The primary technological concern for such cognitive radio architectures, whether it be for wideband sensing procedures or wideband multi-band communication mechanisms, is the ability to design linear and spectrally-agile components and architectures in the radio-frequency front-end of the transceiver.

One foreseen demonstration scheme will use a WiFi primary network as testbed environment. A set of radio demonstrators, each playing both the role of secondary network terminal and wireless sensor will constitute both the secondary network and the wireless sensor network. The traffic will be captured and analyzed from primary network side, and the effects and degradations caused by the secondary network due to cognitive transmission will be measured. The improvements in the spectrum use will be also monitored. This demonstration is depicted on Figure 4.

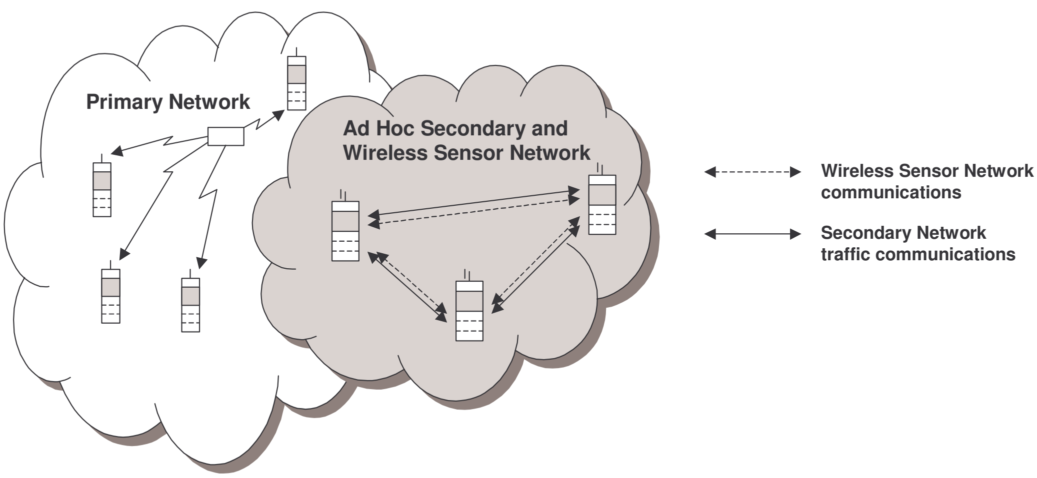

Figure 4: Sensor Network aided Cognitive Radio demonstration scenario

Different demonstration architectures may be foreseen for the processing of the sensed spectrum usage information. In the first step the envisioned system may be simplified by performing this computation in a dedicated fusion centre, connected to the terminals by a fixed network. Then, in a second step, a system with distributed information processing will be demonstrated to prove the communication capabilities of the sensor network.

5. Acknowledgement

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6. Conclusions

Considering the challenges raised by cognitive radio, the use of wireless sensor networks appears as a crucial need to achieve satisfactory results in terms of efficient use of available spectrum and limited interference with the licensed users. As described in this paper, the development of the Sensor Network aided Cognitive Radio technology requires the involvement and interaction of many advanced techniques, including distributed spectrum sensing, interference management, cognitive radio reconfiguration management, cooperative communications, end-to-end protocol design and cross-layer optimisation.

One target scenario is the nomadic broadband in urban and suburban areas, for which significant potential is expected: the Sensor Network aided Cognitive Radio technology will be best suited to provide non real-time services like web browsing and video downloading. Our objective is to promote the development of the technology by providing significant theoretical results and associated simulations in the relevant areas and by delivering a proof-of-concept scheduled by year 2010.

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