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EXECUTIVE SUMMARY

The aim of this document is to investigate the requirements towards the interfaces between sensing, interference management and secondary network access control in cognitive radio networks based on SENDORA Wireless Sensor Network aided Cognitive Radio approach, and to ensure the convergence of the system design efforts in WP4 on interference management and in WP6 on sensor network design.

We overview the control functions for the sensing, interference management and secondary network control, and discuss how these control functions can be implemented in the functional entities of the wireless sensor network and the secondary network. We discuss the possibilities of different levels of centralization of the two networks and the requirements for interfacing them under different architectural options. We conclude that the definition of a general sensing-interference management interface may be possible, while the main challenge comes from the various implementation possibilities of the interference management function.

Then, the deliverable describes the architectural choices performed for concrete implementations in SENDORA, both for system simulation and demonstrations, among the several options addressed by the architecture study.

The document defines the basic functionalities sensor and secondary networks have to provide for collaboration, and the information to be exchanged over the general interface. Finally we discuss the possible goals of standardization in the area.

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ACRONYMS

Acronym	Meaning
BS	Base Station
CH	Cluster Head
CPCH	Cognitive Pilot Channel
CSCH	Cognitive Sensing Channel
FC	Fusion Centre
HN	Home Node
QS	Query Session
SN-CH	Secondary Network Cluster Head
SNet	Secondary Network
SNet-E	Secondary Network Entity
STx	Secondary Transmitter
SU	Secondary User
WSN	Wireless Sensor Network

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1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

The purpose of this document is to analyse sensor network and cognitive radio cooperation principles. The goal is to study and describe what type of information has to be interchanged between the secondary users and the Wireless Sensor Network (WSN) in SENDORA system. The information to be exchanged should depend on the requirements and the capabilities of interference management and secondary network access control (defined in WP4), on the capabilities of spectrum sensing (investigated in WP3) and should affect the sensor network protocol design (addressed in WP5 and WP6). Therefore the main goal of this document is to summarize the possible options of and the requirements towards this cooperation, and to ensure that the different WPs provide building blocks of the cognitive radio system that can interoperate.

In this deliverable we define the three functional blocks of the cognitive system, the secondary communication control, the interference management and the sensing control. We show how these functional blocks can be assigned to the physical entities of the WSN and the secondary network (SNet), and how this assignment of functions affects the interfacing of the physical systems. We discuss possible control architectures, including fully centralized, cluster based and distributed ones and show how sensor networks and S Nets with different architectures can be interfaced.

We show how the interface definitions are applied in the WP6 sensor network design, and WP7 system level simulator and demonstrator activities, that combine the results of the various WPs.

Finally, we discuss the challenges of the definition of a general interface applicable to various wireless sensor networks, and primary and secondary network technologies. We define the general requirements on the sensor and S Nets to ensure cooperation and discuss the needs and preferable approaches of standardisation in the area of cognitive communication.

1.2 THE DEVELOPMENT OF THE DOCUMENT

The first version of this document was delivered in M24. It presented the main building blocks of the sensing-SNet interface, discussed the different architectural options for cognitive channel access control and cooperative sensing. In the first version of the deliverable, we concluded that the definition of a general architecture independent interface might be possible. After further analysis, in this final version, we identify the need for *two functional interfaces*.

In fact, the final version of the document introduces functional blocks, where the secondary access control and the interference management are separated, a change that reflects the results of the WP4 activities on interference management. The final deliverable also includes a discussion on the implementation of the hybrid architecture, a more detailed description of the basic requirements towards the sensing infrastructure and the cognitive network and a high level description of the general sensing- SNet interface.

The functional entities can then be mapped into physical entities according to the network architecture selected. Functional entities may also be implemented in a distributed way in several physical entities.

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1.3 DOCUMENT VERSION SHEET

Version	Date	Description, modifications
1.0	2010.01.15	First version, internal to the consortium, defining the basic cooperation principles.
2.0	2010.07.30	Final version.

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2 BASIC ELEMENTS OF THE COGNITIVE RADIO SYSTEM

Let us first summarize the main operation principles of cognitive radio networks, including the main functions as secondary access control, interference management and the spectrum sensing needed to provide spectrum availability information.

2.1 SECONDARY NETWORK ACCESS CONTROL

We consider the scenario when a cognitive SNet would like to use the frequencies that are allocated to a primary system, but are temporarily idle. The input for the access control is the set of frequencies that are temporarily available for secondary communications. Once these frequencies are known from the SNet, it has to perform channel access control similar to any wireless networks. The difference is that now the set of frequencies to be used is limited, temporary, and also, for each frequency, a maximum transmission power is given that can be used without causing interference in the primary network. To increase efficiency, secondary access control may include different forms of temporal power control and beamforming.

Since the SENDORA project is not focused on a specific type of secondary network, we have assumed that the access control decision architecture of the SNet can be centralized, distributed or a mix of these, and seeked for the identification of the common principles, as well as the possible differences, that enable the WSN-aided cognitive radio paradigm with such different SNet assumptions.

In the fully centralized case, all control parameters are chosen in a centralized manner for all secondary units, while in the distributed case the decision is made locally in the secondary units. The main practical differences between these architectures are:

- the information available to the decision process,
- the related communication requirements within the WSN and the SNet,
- and the resulting system performance.

Due to this, even in a realistic centralized architecture, some of the decision processes will be delegated to the secondary units to save communication resources.

Since in a realistic networking scenario many SNet may visit the same area, the access control may include functions to avoid collision among SNet.

Although the design of secondary access schemes is not in the scope of the SENDORA project, some solutions are reported in WP4 deliverables.

2.2 INTERFERENCE MANAGEMENT FOR COGNITIVE TRANSMISSION

The cognitive operation in the SNet requires interference management with the objective to keep the interference caused by the SNet to the primary network under a predefined level, and at the same time maximize the throughput of the SNet. In SENDORA, WP4 is dedicated to the design of such interference management methods.

The interference management takes the frequency usage measurements (provided by sensing means) as input and provides the selection of frequencies the secondary system can use for communication, the allowed transmission power for these frequencies, and the time interval the frequencies are available for secondary use. For an efficient interference management the frequency usage information has to be accurate and timely.

The interference management functionality requires knowledge of the signal levels within the system to base the control decisions upon. It uses the sensing functionality of the cognitive system to acquire this information, typically both on primary and secondary signals. It then uses the sensing information

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in combination with other side information, typically on primary system behaviour, parameters and location, to provide frequency availability information for the secondary access control functionality.

From a whole system level viewpoint, and in a scenario where multiple secondary networks are allowed to perform cognitive access to the same licensed band(s) in the same area, interference management may even include functions to help their coexistence, that is, limiting the interference transmissions that parallel SNet cause to each other.

2.3 SENSOR NETWORK AND COOPERATIVE SENSING

WP6 is responsible for the design of the WSN for the fixed WSN case and for the case of the ad-hoc sensor network (cases introduced in deliverable D2.1). Some knowledge on the WSN protocol design is necessary to construct the SNet-WSN interface, this is summarized below.

The frequency usage information for interference management is provided by a WSN that can be a dedicated, fixed sensor network, an ad-hoc network of secondary users with sensing capabilities, or a mix of those. The WSN uses a low bandwidth dedicated control channel to interact with the SNet and for WSN internal communication.

The considered environment includes one or more primary networks operating in given frequency bands. The primary systems may access these bands using some kind of frequency division multiplexing. The SNet operating in the area can access the sub-bands that are idle in the area of the SNet operation. To provide reliable estimate of the spectrum usage, cooperative sensing is performed, that is, several sensors cooperate to come up with a common estimate.

The goal of data transmission within the sensor network is twofold. Local data exchange may be necessary to support cooperative sensing at each individual sensor, and convergecasting from all or a group of sensors is needed to collect the spectrum usage information needed for interference management. Several options are possible. These two processes can run in sequence, cooperative sensing can be performed during convergecasting, or the pure local information can be collected, and in this case distributed sensing is performed after convergecasting, maybe in the SNet.

As discussed in D6.2, in the case of fixed dedicated sensor networks, the collection of sensed information within a given region is a deterministic process, and since the WSN topology is known, a fixed TDMA based information fusion is efficient. In the case of the ad-hoc sensing infrastructure, where sensing is provided by the SNet nodes, an entire ad-hoc network protocol stack is required, where the cooperating nodes are discovered and the channel access and convergecasting process is optimized according to the topology of the ad-hoc network.

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3 THE SENDORA NETWORKING SCENARIOS

The D2.1 - “Scenario descriptions and system requirements” deliverable defines indeed two main cases of SENDORA architectures: the WSN aided cognitive radio system and the ad-hoc cognitive radio system, where sensors are integrated in the secondary terminals. In addition, it introduces the hybrid architecture, where both the dedicated WSN and the integrated sensors perform sensing. The three architecture cases are detailed below.

3.1 WSN AIDED COGNITIVE RADIO SYSTEM

In this scenario a WSN is implemented and maintained to provide spectrum availability information in the area and over the frequency bands where cognitive operation is allowed. This WSN may be operated by the owner of the spectrum (and the owner of the primary networks in the area) or by an independent company or organization (potentially a regulation body). The cognitive SNETs operating in the area have to follow the rules defined by the cognitive service provider.

Since the WSN and the SNET are operated by different actors in many scenarios, this interface has to be well defined, and general enough such that the operation of the WSN is transparent to the SNET and vice versa. This transparency is the main objective of the interface design in the SENDORA project.

3.2 AD-HOC COGNITIVE RADIO SYSTEM

In this scenario the secondary users (or part of them) have sensing functionality and form an ad-hoc WSN for spectrum sensing. Thus, the SNET can operate without any assistance from an independent sensing infrastructure. The SNET users exchange information about the frequency availability in the area (on the dedicated band) and decide how to use the available spectrum bands. In this case the sensing and the SNET operations are tightly coupled. Still it seems to be a reasonable approach to implement an internal interface between the sensing and the SNET control. This interface may make it possible to improve some of the functions without changing the entire architecture.

3.3 HYBRID COGNITIVE RADIO SYSTEM

This scenario is the combination of the previous two scenarios: a fixed, dedicated sensor network is deployed in the area of cognitive operation, but even secondary nodes sense the spectrum and contribute to the spectrum sensing task. In principle the cooperation can be performed on two different levels:

1. Independent sensing

The two cooperative sensing processes run independently, and channels that are detected free both by the fixed sensor network and the ad-hoc network of secondary users are available for secondary transmission. This cooperation is easy to provide, however, the benefit is not significant, since both sensing infrastructure should be able to perform reliable cooperative sensing.

2. Hybrid sensing

Local sensing measurements from both the dedicated sensors and the secondary nodes are considered for cooperative decisions. The accuracy of the cooperative decision is increased compared to the simple WSN-aided or ad-hoc cases. The implementation is more complex, since an interface for cooperative sensing is needed.

To implement hybrid sensing, we have to decide which sensing infrastructure, the dedicated fixed WSN or the sensor network formed by the ad-hoc network secondary nodes is responsible for the

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spectrum decisions. If the fixed WSN is responsible, then the ad-hoc sensors have to be integrated in the otherwise rigid sensing aggregation process. In the opposite case the ad-hoc network has to be able to discover the fixed, dedicated sensors and collect their local decisions.

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4 FUNCTIONAL ARCHITECTURE

Based on sections 2 and 3 we can conclude that the SENDORA cognitive radio system consists of three functional entities: sensing, interference management and SNet control, and two physical units, the WSN and the SNet.

One of the ambitions of the SENDORA project is to draw conclusions and indications for further development that are not limited to a specific implementation. Therefore, in the following, we first describe the interactions among the involved *functional* entities, rather than the physical units composing the networks.

The involved functional entities (depicted on Figure 1) are called:

- S-Net communication (SNet-COM),
- Interference management (IF-MGMT),
- Sensing (SENSE).

The SNet-COM functional block is comprehensive of all the operations needed to implement *the communication aspects* of the cognitive radio network protocol stack, such as agile physical layer, cognitive MAC, routing (if applicable), and so on.

The SENSE block contains all the functions that are specific of the spectrum sensing tasks: the selection of sensors to collect information from and the channels to be scanned (including potentially parameters like the detector type, the sensing time,...), the processing and collecting of the local sensing results, and, possibly, the implementation of cooperative sensing in either a distributed or centralized way, this last option including inter-sensor communication on a dedicated radio resource.

The IF-MGMT functional entity can contain the following internal functionalities (functional sub-entities):

- Measurement pre-processing, e.g.,
 - linear/non-linear combining (cooperative sensing)
 - compression
- estimation of interference to primary
 - use of side-information (location related),
- secondary transmission parameter optimization
 - estimation of allowed transmit power per frequency for a secondary user,
 - support for multiple secondary systems.

Note that, whereas the SENSE functions and the SNet-COM function can be straightforwardly associated with the WSN and SNet physical entities respectively, the IF-MGMT functions can eventually be spared among the two of them or, if the WSN supports more than one SNet, several functions can be reserved to the WSN physical entity(ies) and others delocalized to the SNet(s) ones. The result is that the physical interface WSN—SNet is in reality in many cases an internal interface of the functional entity IF-MGMT.

4.1 FUNCTIONAL INTERFACES

The SNet-COM – IF-MGMT interface is a resource allocation interface, over which resources are requested and granted. The IF-MGMT—SENSE interface is a measurement interface, where

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measurement patterns are configured, and measurement results reported. The upper part of Figure 1 depicts the resource request flow in the functional blocks, while the lower part depicts the resource allocation flow based on sensor measurements.

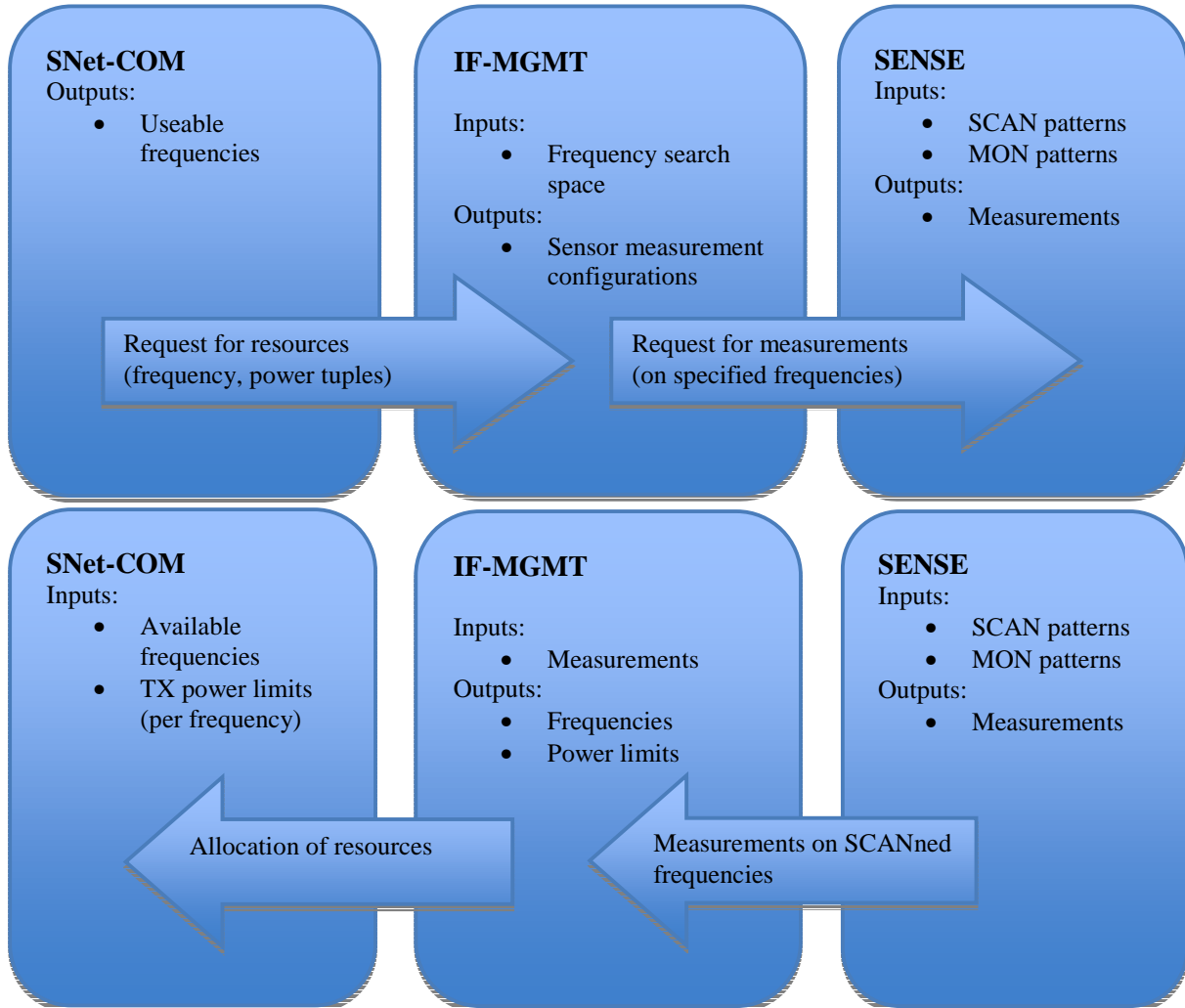


Figure 1: Functional blocks and message exchanged across their interfaces.

We can then outline three examples for dividing the IF-MGMT functionality between the WSN and SNet. The first two are the extremes where IF-MGMT is fully contained in either the SNet or the WSN, while the third one is an intermediate example of a division of tasks between the WSN and SNet:

1. SNet contained IF-MGMT.

The SNet–WSN interface is a measurement interface, and the SNet provides all further system optimization and resource management.

2. WSN contained IF-MGMT.

The SNet–WSN interface is a resource management interface and the WSN provides all resource allocations for the SNet.

3. WSN contains parts of the IF-MGMT functionality to provide

- a) measurement pre-processing,
- b) basic resource allocation for multi-SNet support.

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The first will ensure that the physical WSN-SNet interface will not consume excessive resources due to non-intelligent sensor measurement reporting, the second that potential multiple S-Nets can co-exist without explicit collaboration.

4.2 FUNCTIONAL COGNITIVE ACCESS PROCEDURE: THE QUERY SESSION

The above described functional architecture can be seen as a *logical* framework within which the cognitive channel access procedure is carried out. In the following we identify the abstract exchange of information, that we call a *query session*, which is required between the aforementioned functional entities to complete the cognitive cycle, i.e. to allow secondary users to access the available bands. It is important to emphasize that the nature of the following description is abstract, in the sense that it is valid for every possible network configuration. What differs from one configuration to the other is how the abstract functionalities and messages are physically implemented through real devices.

From a system level point of view, we categorize three, possibly coexisting, levels of interaction among the functional entities, considering the time-scale of the spectrum occupation dynamics to which the information exchanged refers. In particular we distinguish:

- a) *A large-time scale level:* at this level, the information exchange allows to set up suitable system parameters for a secondary network willing to enter the area of cognitive operation. For example, suppose that the secondary devices are able to operate over a multitude of primary system bands. Then, the IF-MGMT identifies the most suitable band, given the kind of traffic the SNet is going to generate and the current primary radio scene.
- b) *A medium time-scale level:* this level represents the feeding provided by IF-MGMT on channel availability in a statistical sense. Frequencies, or transport channels if the operational system band is an operator one¹, are classified by the SENSE unit through their primary occupation statistics (e.g., in the simplest case, the percentage of time). Clearly the SNet-COM will invoke some sort of probabilistic access techniques in order to minimize the interference probability.
- c) *A small-scale level:* in this case channel availability information refers to instantaneous channel occupation from the primary rather than to a statistical characterisation.

Which of the above type of information exchange actually takes place depends on the specific scenario considered, i.e. on the characteristics of both primary and secondary networks (topology, network architecture, node density, traffic load, and so on), and on the capabilities of the SENSE unit to provide the required information. In a complex scenario, the three of them can coexist.

The starting point of a query session is a request arising from the SNet-COM functional unit towards the IF-MGMT unit. This message, essentially, tells the IF-MGMT unit that the SNet-COM needs information on the availability of resources. The message is composed of two attributes, the **type of information requested** and the **side information** provided for resource identification.

In Table 1 we summarise the properties of three types of query sessions corresponding to the three levels of information exchange described above, specifying the following **attributes**:

- i*): type of resource requested,
- ii*): side information provided.

¹ When the primary network is a cellular operator, it may be convenient to align the resource allocation for secondary users to the transport channel, which are a sequence of physical resource blocks with a predefined frequency hopping pattern inside the time-frequency grid composing the physical layer frames of the primary network technology standard, rather than to physical frequency. Clearly, to do this, the IF-MGMT must have knowledge of the specific patterns.

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Query Sessions Attributes		
Query Session Type	Type of information requested	Side information provided
a) SNet-COM connects to the IF-MGMT unit to start an interaction, or to update the parameters of an existing interaction.	<ul style="list-style-type: none"> • A System (sub)-band to be used for cognitive access within the set of bands that are accessible through the technology of secondary users. • The overall expected throughput that the IF-MGMT can guarantee over the provided system band. 	<ul style="list-style-type: none"> • Statistical characterization of the number of SNet users. • Region over which the SNet is operating. • Characterization of the interference impact generated by potential SNet transmissions in the spatial domain; essentially the range of transmission ranges that secondary users may use in their transmissions. • Large time-scale statistical characterization of the traffic demand by secondary users
b) SNet-COM asks for one or a set of available resources, either for a specific STx, when the IF-MGMT is in charge of the WSN, or for a group of STxs, when IF-MGMT is in charge of the SNet. Resource availability is to be understood in a statistical sense.	<ul style="list-style-type: none"> • A channel or a set of channels that are not being used, or are being used with a low intensity, by primary networks in a region of interest. • Average or peak power constraints that STXs must be subject to. • Constraints on the percentage of time and/or the time dynamics with which secondary users can access the provided channels 	<ul style="list-style-type: none"> • Statistical characterization of the interference impact generated by the STx transmissions in the spatial domain; essentially the range of transmission powers that secondary users may use in their transmissions and, if available, the location of the secondary users. • Statistical characterization of the traffic demand by the secondary user at a medium time scale, e.g. at the flow level.
c) SNet-COM asks for a resource for immediate, deterministic, use. The resource availability is deterministic.	<ul style="list-style-type: none"> • One or a set of channels made available to secondary users for immediate access. Secondary users access then the channel assuming that it is not currently being used by primary users. 	<ul style="list-style-type: none"> • The maximum transmission power the STXs may use and, if available, the location of the transmitters. • Length of the single packet or of the packets inside the stream.

Table 1: Query Sessions attributes

On the basis of the received requests (possibly of different types) received across the SNet-COM—IF-MGMT interface, the IF-MGMT unit drives the spectrum sensing activities of the SENSE unit, through suitable signalling messages. Measurements, or more likely a processed version of them, are

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then sent back by the SENSE unit and elaborated by the IF-MGMT interface to compute the desired resource assignment for secondary users.

It has to be noted that the mapping between the requests coming from SNet-COM and the messages exchanged on the IF-MGMT—SENSE interface is not necessarily one-to-one: the IF-MGMT unit can in fact aggregate more requests, e.g. those received in a given time interval, to compute an aggregated request for measurements to the SENSE unit. In fact, the capability of the IF-MGMT to handle multiple query sessions in a joint manner is crucial for the implementation of multiple access from secondary users, since the resource allocation is closely related to the effect secondary transmissions would have on primary ones, which puts constraint on how secondary transmitters can use that channel.

Then, the computed available resources are sent back to the SNet-COM unit to complete the query session, or a set of query sessions in case of aggregate processing.

Besides taking measurements on the primary signal presence, the SENSE unit also performs the important task of monitoring (MON) the *secondary* signals and triggering an interrupt towards the IF-MGMT when it detects that the secondary activity is violating the constraints imposed by the agreement between primary and secondary networks. This task is also driven by the IF-MGMT unit through suitable control messages that indicate to the SENSE unit the patterns of the channels to be scanned for secondary activity that, in turn, depend on the resource allocation the IF-MGMT has provided.

The last important issue, with which we conclude this section, is that both the IF-MGMT unit and the SENSE unit may act in a proactive way, i.e. they may keep on elaborating possible outputs and sending them to the SNet-COM or IF-MGMT, respectively. This capability is useful to save overhead when the resource allocation demand coming from SNet-COM stays homogeneous and intense for a certain amount of time. Again, the details on which parts of the system are reactive or proactive depends on the specific implementation, see e.g. Section 6.2.

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5 IMPLEMENTATION IN THE SENDORA PROJECT

Given the three possible system architectures described in Section 3, and having described the functional characteristics of sensing, secondary access, and interference control, we can now define the architecture from a physical point of view, and describe the blocks that play a role in the interaction between WSN and SNet.

Secondary access control based on cooperative sensing requires communication between the secondary transmitters and the sensing points. In the SENDORA system, a low bandwidth control channel is considered available to transmit these control messages (as specified in D2.1 deliverable). Once the availability of primary channels is discovered, even the control communication can be moved to one of these channels. It is important to note that there are no multiple control channels. The communication between the sensing nodes performing cooperative sensing has to use the same control channel as the communication between the secondary units and the sensing nodes. Following the terminology used in the demonstrator, the Cognitive Pilot Channel (CPCH) is used for message exchange over the sensing and secondary network interface, and the Cognitive Sensing Channel (CSCH) is used for sensing information fusion within the sensor network. The CPCH and the CSCH shares the same band.

We resort to the description of the implementation of a type c (small time scale) query session in a WSN-aided Cognitive Radio scenario. For other types of query sessions and/or scenario, the same kind of considerations, suitably adapted, apply.

5.1 THE PHYSICAL ENTITIES AND THE QUERY SESSION

The physical entities communicating in the Query Session (QS), as shown on Figure 2 are the following:

- 1) A Secondary Network Entity that we denote as SNet-E that opens the session from the side of the SNet.
- 2) A node of the WSN that we call WSN Home Node (HN), to which the SNet connects (or is permanently or semi-permanently connected). The HN initiates the QS from the WSN side.
- 3) A STx that wants to use portions of the shared system band for its transmission. The STx may, or may even not, coincide with the SNet-E.

The interface between the SNet and the WSN is between the entities SNet-E and HN.

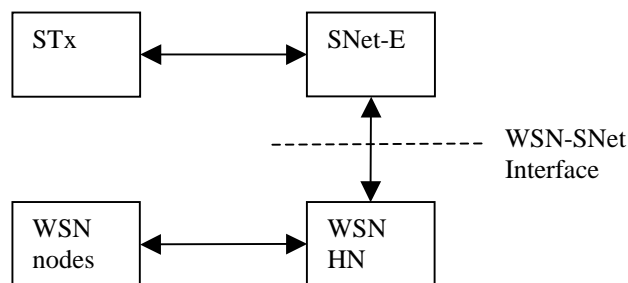


Figure 2: The WSN-SNet Query Session

The QS includes a sequence of message exchanges.

1. Messages exchanged for building the SNet-E – HN connection

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2. Messages exchanged periodically to update the frequency usage information and optionally the secondary channel usage
3. Messages to tear down the session.

The D7.2 and D7.3 deliverables contain detailed examples of the QS message exchanges for the demonstrator scenarios. The corresponding QS have been implemented and emulated on the demonstration protocol stack.

5.2 INFORMATION EXCHANGE OVER THE WSN-SNET INTERFACE

The information exchange over the WSN-SNet physical interface depends then partially on the implementation of the IF-MGMT functionality.

The SNet (more specifically the SNet-E) has to inform the sensor network (through the HN) about

- its radio capabilities (e.g., the frequencies it is able to use),
- its transmission needs, location and maximum transmission power information if available.
- optionally the frequency bands the SNet is using in the following period to relax the sensing constraints.

Based on this information the WSN can scan (SCAN) the primary frequency bands not used by the SNet for available frequencies and can monitor (MON) the primary frequencies used by the SNet, so that it can detect if the primary network starts to use those frequencies.

The information above has to be provided in different frequencies. Radio capabilities have to be provided at the beginning of a QS. Transmission needs have to be refreshed as they change. Information on the used frequencies has to be provided according to the sensing periods.

The HN of the WSN has to provide:

- service information to easy SNet-E connection (e.g., pilot signal in distributed systems),
- synchronization information for SNet silent periods and for the reallocation of frequencies at SNet connection setup,
- periodic information on the spectrum usage in the target area.

The information exchanged periodically over the SNet-WSN interface (secondary transmission needs and primary spectrum usage) depends significantly on the way the IF-MGMT is implemented. Considering the examples in Section 4, the exchanged information is the following:

1. SNet contained IF-MGMT.
 - The SNet requests measurements specifying the area (location and max transmission power) and the set of frequencies.
 - The WSN provides vectors of measurement data.
2. WSN contained IF-MGMT. The SNet-WSN interface is a resource management interface and the WSN provides all resource allocations for the S-Net.
 - The SNet requests frequency resources, optionally giving location and maximum transmission power information, and bandwidth needs.
 - The WSN provides the vector of available frequencies and related allowed transmission powers.
3. The WSN contains IF-MGMT functionality to provide
 - a) measurement pre-processing

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- similar as point 1, but the measurement information is pre-processed, e.g., cooperative sensing or aggregation is performed within the WSN.

b) basic resource allocation for multi-SNet support

- similar as point 1, but only a subset of free frequencies are reported as available for a SNet, to avoid collision among SNetS in the same area.

The SNet contains IF-MGMT functionality to perform the matching functions

- frequency resource allocation and access control based on pre-processed sensing results.

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6 WSN DESIGN DECISIONS

The flow of control traffic and the flow of sensing information in the WSN and in the SNet are affected by how these systems are designed. Design decisions in the WSN and in the SNet are necessarily independent from each other in the case of the dedicated WSN, while can be co-optimized in the case of the ad-hoc cognitive network.

6.1 CENTRALIZED, DISTRIBUTED OR CLUSTERED CONTROL

The SENDORA architecture includes control functions on several levels: the control of cooperative sensing, the control of channel access within a secondary network, and the control of channel access among secondary networks residing in the same area. In this section we give some examples of the possible levels of centralization, as shown on Figure 3. In this section we explain what centralized and distributed decision making means, for the specific case of sensing control. The conclusions hold even for the other control functions to be implemented.

6.1.1 Centralized control

When centralized sensing control is applied, there is a dedicated fusion centre (FC) in the system that collects both the frequency measurements and the requests from the secondary networks and allocates frequencies (with bandwidth, power and time interval) for the secondary communication. Centralized control can be applied in both the fixed WSN and the ad-hoc scenario. In the first case there is a dedicated fusion centre, in the second case the ad-hoc network selects a node that acts as a FC for frequency allocation. The advantage of a centralized control is that the decision process is based on calculation at the central unit and the sensing performance can be superior to the distributed case. The disadvantage is that all communication has to go through the central entity, which is a single point of failure, also the communication takes time and transmission resources. In addition, the WSN has to be designed such a way that enough transmission resource is available close to the FC and the power supply of the sensors forwarding many sensing and control information is solved.

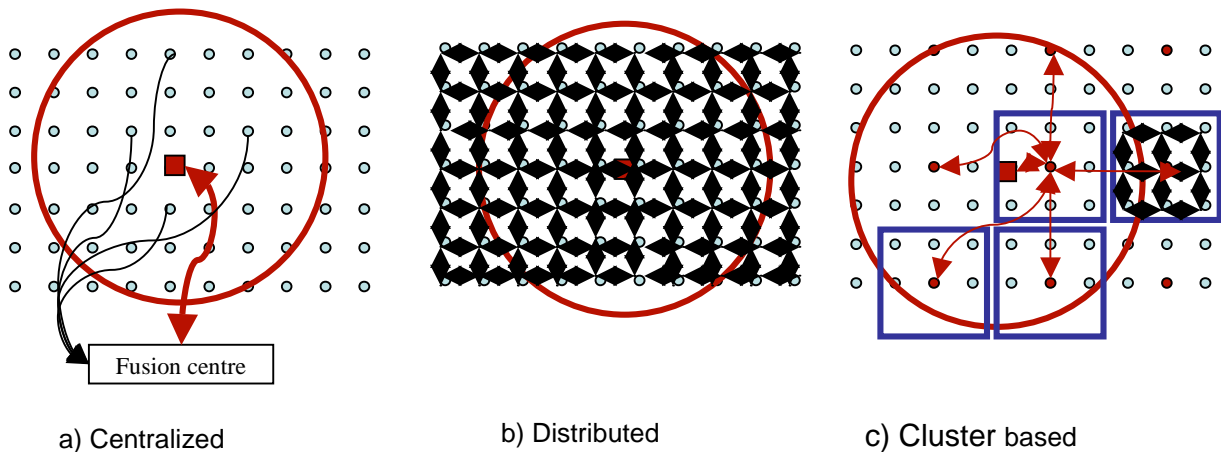


Figure 3: Control architectures to collect sensing information and control the secondary unit transmission

6.1.2 Distributed control

In the case of distributed control there is no single central FC, but each sensor provides information directly to the secondary units requesting frequency. Again, distributed control is possible both in the fixed WSN and in the ad-hoc cases. The advantages are lower control delays and communication needs between the WSN and the secondary network, and increased robustness. However, additional inter WSN communication is needed to inform all sensors about the spectrum availability in the area

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around it. In addition, a distributed protocol has to be defined among the secondary networks or among the sensors to avoid allocating the same frequency to more than one network in the same area.

6.1.3 Cluster based architecture

Clustered architectures are often proposed for WSNs to balance communication needs and control complexity. In our specific case a cluster based architecture means that there are several FCs implemented in the network (we will use the term WSN-CH), each of them being responsible for collecting information in a given area – the cluster. When a SNet arrives to the area of cognitive operation it requests frequencies from the nearest WSN-CH. If the SNet target interference region can reach outside the respective cluster, the WSN-CHs have to cooperate to define the set of available frequencies.

6.1.4 Design decision

It is difficult to compare the possible solutions – that is the level of centralization required – without the detailed evaluation of the inter WSN and WSN-SNet communication needs, without performance evaluation studies, and without considering the exact requirements of interference and channel access control.

6.2 PROACTIVE OR REACTIVE SENSING IN THE WSN

6.2.1 Proactive sensing

In the proactive sensing case the spectrum availability information is updated periodically independently of the secondary activities. All sensors measure all the time according to a given sensing strategy and send information to the unit that aggregates sensing information. When a SNet needs to communicate, it can receive an up-to-date list of available frequencies without delay.

6.2.2 Reactive case

In the reactive case, the frequency search is initiated on demand in the sensor network by the SNet that needs to communicate and requests frequencies. The SNet contacts the respective unit in the sensor network. The sensor network initializes the spectrum sensing by activating the sensors that should provide spectrum availability information given the secondary network input.

Since the spectrum measurements are done to serve a specific secondary request, the activated sensors continue the spectrum measurements and update the availability information periodically. The set of active sensors can be considered to be static, or can be continuously optimized as the secondary transmission parameters or the primary activity changes. The optimization of the set of active sensors is part of both the IF-MGMT and the WSN protocol design optimization.

6.2.3 Design decision

Proactive and reactive sensing might be selected based on the load in the secondary system. At low secondary activity there is no need to sense all the time, everywhere, and the energy spent for sensing and communication of the sensed data can be decreased. At high secondary activity the additional control overhead of reactive sensing might be significant, while due to the high frequency of requests most of the sensors have to sense anyway. In that case proactive sensing may be more efficient.

Note that reactive sensing requires a set-up phase where the sensors that have to participate in the interference management are activated. If this set-up delay is not acceptable, proactive sensing may be necessary. However, in most cases this initial delay will not be a problem – many classical communication systems have similar set-up delays from classical telephony to TCP based data transmission. The nature of the sensing (proactive vs. reactive) does not affect the QS, and the different cases are addressed in the D6.3 deliverable.

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7 WSN AND SNET ARCHITECTURE OPTIONS

We defined three functional entities, the sensing, the interference management and the secondary communication, and showed how these entities are assigned to the sensor and to the secondary network. We defined the physical entities of the secondary and the sensor networks that communicate with each other to exchange the information needed for the functional entities.

We discussed the different architecture options for the sensor and secondary networks, including centralized, cluster based and distributed control. Since the architecture for the sensor and for the secondary network may be selected independently, we have to evaluate, how the different architectures can interoperate.

In addition we have to discuss the issue of synchronization of sensing and secondary communication intervals and the localization of SUs, both as transmitters and as ad-hoc sensors. As for synchronization, we propose that the sensor network defines the sensing and transmission schedule and provides this information for the SNet. This solutions ensure that the WSN can effectively assist the operation of several secondary networks and can ensure the reaction time limits given by the primary network technology. Considering the SU localization, we assume that SUs are equipped with GPS, or some localization protocol is implemented, as described in D6.2, when SUs can determine their location based on the information received in the pilot signals of some sensors.

Next we discuss the communication and synchronization requirements of the different sensing and secondary network architectures, for the three cases of the dedicated WSN, of the ad-hoc and of the hybrid sensing case.

7.1 WSN AIDED COGNITIVE SECONDARY NETWORK

7.1.1 Sensing

7.1.1.1 Centralized aggregation at the FC within the WSN

This scenario is shown on Figure 3.a. Sensors send their sensing results to the FC. Based on the received information, the FC provides a spectrum availability map. The FC plays the role of the WSN HN.

Communication needs: all sensors with relevant sensing information (relevance depends on the proactive or reactive sensing strategy) send their sensing results to the FC. In the case of reactive sensing and for the monitoring of channels used for secondary communication the FC sends sensor specific control information to individual or group of sensors. The transmission paths are long and are determined by the area of secondary operation (or the distance of FCs if more than one are used). Fusion and control trees might be optimized, both in terms of energy and of sensing efficiency.

Synchronization needs: the FC has to provide synchronization information for the sensors, to define scanning, monitoring and intra-WSN communication time intervals.

7.1.1.2 Cluster based sensing

As shown on Figure 3.c, the WSN in this case includes dedicated WSN cluster heads (WSN-CHs) that collect sensing information from the sensors belonging to their cluster. The set of CHs and the cluster boundaries are pre-defined. The WSN-CHs can calculate a spectrum availability map in their cluster. CH to CH information exchange is needed if the SNet target interference region includes several clusters. The WSN-CHs play the role of the WSN HNs when contacted by a SNet-E.

Communication needs: All sensors send sensing information to the predefined CHs, CHs may have to send control information to the sensors in the cluster. CHs have to communicate to be able to provide

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a spectrum availability map that is larger than the cluster size. The transmission paths length depends on the cluster sizes.

Synchronization needs: As in the centralized case all sensors have to be aware of scanning, monitoring and communication time intervals. This synchronization is done by all CHs.

7.1.1.3 Distributed sensing

Distributed sensing is shown on Figure 3.b. This solution is similar to the previous one, but any of the sensors can become temporal WSN-CH, when contacted by a secondary network unit. Then the sensor acts as WSN-CH and collects sensing information from all the sensors within the SNet target interference region. Consequently, any of the sensors can be contacted by an SNet-E and may play the role of the WSN HN.

Communication needs: the sensor that becomes a temporal WSN-CH has to send control messages to the sensors in the area of SNet communication, and sensors have to fuse sensing information to the temporal CH. Again, the control and fusion trees may be optimized. The transmission paths length depends on the communication range of the secondary network.

Synchronization needs: synchronization of the sensors has to be maintained through a distributed algorithm. Other control functions, e.g., pilot signals of sensors to advertise the service for the SNet, can be used for this purpose.

7.1.2 SNet internal control

7.1.2.1 Centralized with an SNet base station (BS)

The SNet has a specific coordinating node, commonly addressed as base station (BS). Based on the information received from the WSN the BS allocates orthogonal resources to the communicating secondary units, or runs any common channel access protocol. The BS plays the role of the SNet-E.

Communication needs: BS - secondary unit communication is needed for the channel access control.

Synchronization needs: the SNet has to synchronize to the WSN schedule. The BS receives this information from the sensor network and applies it when scheduling the SNet transmissions.

7.1.2.2 Cluster based with SNet cluster heads

The secondary network is structured into clusters. Each cluster head (SN-CH) retrieves spectrum availability information from the WSN and controls the channel access of nearby secondary units. The SN-CHs play the role of the SNet-E.

Communication needs: SN-CH and SU communication for channel access control and communication among SN-CHs for access coordination.

Synchronization needs: each SN-CH has to control the channel access within its cluster based on the received synchronization information.

7.1.2.3 Distributed SNet

The SUs of the SNet ask for spectrum availability information individually. SUs form a flat mesh and run a distributed protocol to decide about the channel access in a distributed way (e.g., contention based protocols for meshes). Each of the SUs may play the role of the SNet-E.

Communication needs: this requires a distributed protocol among the SUs to control channel access.

Synchronization needs: each communication SU receives synchronization information directly from the sensor network.

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7.1.2.4 Hierarchical channel access coordination

Each pair of SUs in the SNet counts as a separate secondary network, and request frequency on its own.

7.2 AD-HOC COGNITIVE NETWORK

7.2.1 Sensing

7.2.1.1 Centralized at one unit within the SNet

There is one dedicated unit within the SNet that collects sensing information and prepares a channel availability map for the whole SNet. This unit is the HN in the interface architecture.

Communication needs: As in the fixed WSN case, all sensing results have to be communicated to this central unit. Also, this central unit may have to send control messages to all or a set of secondary nodes for reactive sensing and for the monitoring of channels used in the SNet. Therefore, this solution seems to fit best to secondary networks that have a star topology implemented in the link layer.

Synchronization needs: The central unit broadcasts synchronization information over the cognitive control channel for the whole network.

7.2.1.2 Cluster based cooperative sensing

There exist several clusters with cluster heads in the secondary network (SN-CH). Sensing information fusion is done by the SN-CHs, and each of them implements the HN functionality. This solution fits well larger secondary networks with mesh or mesh+star link layer structure.

Communication needs: SN-CHs communicate with the nodes within their cluster to control sensing and receive sensing information. Inter-CH information exchange is needed if a transmission area overlaps with many clusters.

Synchronization needs: the SN-CHs distribute synchronization information among each other and control the secondary units in their cluster.

7.2.1.3 Distributed cooperative sensing

All secondary units broadcast sensing information on the broadcast control channel, which is received and used by nearby nodes. Each secondary unit decides about the available channels within its transmission area. That is, each secondary unit may play the role of a HN.

Communication needs: broadcast messages from all sensors need to be transmitted on the same broadcast channel, together with optional sensing control messages. Additional sensing information exchange may be needed among the nodes, if the broadcasted messages do not reach all nodes that require the information.

Synchronization needs: a distributed protocol is implemented to keep the sensing secondary nodes synchronized.

7.2.2 SNet internal control

7.2.2.1 Centralized at one unit within the SNet

The unit controlling the channel access (BS) receives information about the channel availability from the respective unit(s) according to the previous point, and sends channel access control information to the nodes in the SNet. The control information depends on the medium access control protocol used in the SNet. That is, the BS implements the SNet-E functionality.

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Communication needs: direct communication is needed from the BS to all secondary nodes who wish to communicate.

Synchronization needs: again, the sensing process determines the transmission intervals in the network, and therefore the BS receives synchronization information from the respective unit of the sensing control architecture. The BS then schedules transmissions accordingly.

7.2.2.2 Cluster based

The SNet is divided into clusters, each cluster controlled by a CH. CHs decide about the channel access within the cluster, that is, they implement the SNet-E functionality.

Communication needs: communication for channel access control is needed between a CH and the nodes within the cluster. Additional communication is needed among CHs to avoid interference between clusters.

Synchronization needs: again, the sensing process determines the transmission intervals in the network, and therefore the SN-CHs receive synchronization information from the respective unit of the sensing control architecture. The BS then schedules transmissions accordingly.

7.2.2.3 Distributed control

The secondary nodes form a mesh network and decide about the channel access, in a distributed way, each secondary node implements the SNet-E functionality.

Communication needs: a distributed protocol for channel access control has to be implemented.

Synchronization needs: again, the sensing process determines the transmission intervals in the network, and therefore the secondary nodes receive synchronization information from the respective unit of the sensing control architecture.

7.2.2.4 Hierarchical channel access coordination

Each pair of SUs in the SNet counts as a separate secondary network, and requests frequency on its own.

Sensing and interference management may use similar control architecture in this case, for example, the same units within the SNet – the SN-CHs – can act as HNs and SNet-Es at the same time. In that case the interface is implemented within the SN-CH units.

Since in the ad-hoc network case the same system design deals with sensing and secondary communication, the two control architectures can be harmonized. The same architecture may be preferable to limit the control traffic required to maintain the virtual topology, while different architectures may be selected for sensing and secondary control if the traffic patterns are very different and different architectures are required to limit the aggregate network traffic.

7.3 HYBRID ARCHITECTURE

The two options for the sensing in the hybrid architecture are the independent sensing and the hybrid sensing as defined in Section 3.3. Now we discuss these two options considering the SNet—WSN interface.

1. Independent sensing.

In this case the two sensing architectures – the WSN and the ad-hoc network – perform sensing and generate the map of available frequencies independently. It also means that there are two HNs in this case, one maintained by the WSN, and one maintained by the SNet. The two maps from the two HNs have to be collected by the same SNet-E. It means two parallel interfaces between the SNet and the two sensing infrastructures, as it is shown on Figure 4.a. The QS has to be extended accordingly. The

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cooperative sensing architecture itself follows the options presented in Section 7.1 for the fixed WSN part and in Section 7.2 for the ad-hoc sensing infrastructure.

2. Hybrid sensing.

The fixed and the ad-hoc sensors form one single sensing infrastructure, controlled by the WSN or by the SNet. The spectrum availability map for a QS is generated by a single HN (provided by the WSN or by the SNet). As a consequence, the SNet—WSN interface is not affected. The sensing architecture options follow Section 7.1, if the fixed WSN collects all the sensing results, and it follows Section 7.2, if the ad-hoc sensing infrastructure collects the sensing results. To collect the sensing information from all sensing nodes, message exchange is necessary between the two architectures, that is, a sensing interface have to be defined, as shown on Figure 4.b.

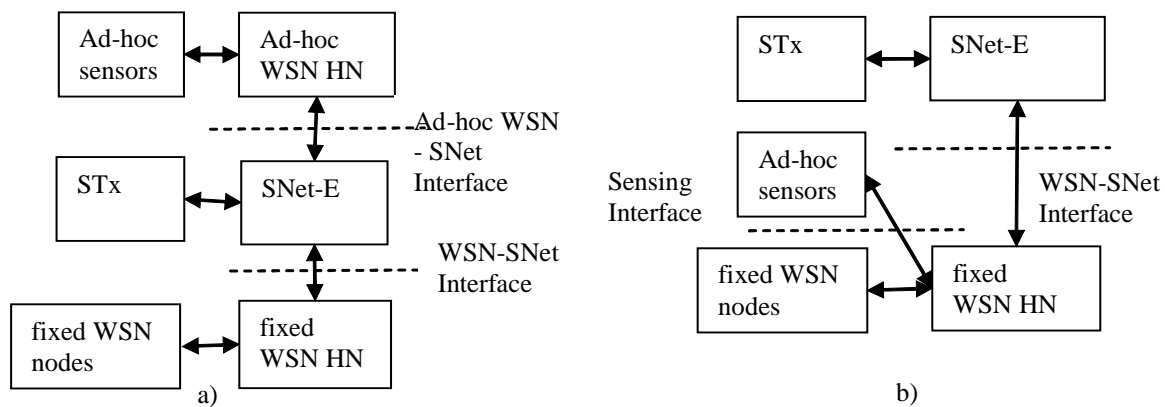


Figure 4: Additional interfaces in the case of hybrid sensing architectures. a) Independent sensing. b) Hybrid sensing controlled by the fixed WSN.

In this section 7, we have described the possible combinations of architectural configurations for the WSN and for the SNet. In the following sections, we focus on the physical interfaces among the two networks, in the cases where the WSN is present, i.e. the dedicated WSN and the hybrid architecture. First of all, in Section 8 we identify some general requirements for this interface, then, in Section 9, we describe how two of the specific architectures and interfaces have been implemented within the project. The first one falls within the dedicated WSN design option with cluster-based WSN architecture, the related activity in the project has its terminal output in the system level simulator. The second one is the hybrid architecture with centralized WSN, which is considered in the demonstrator.

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8 REQUIREMENTS OF A GENERAL SENSING – SECONDARY NETWORK INTERFACE

The aim of the WSN design shall be to serve SNETs with arbitrary architecture – BS based, clustered, or distributed mesh. Based on the evaluation above, it seems that the QS (the sequence of messages exchanged) itself is independent from both the WSN and the SNET architectures.

While the interface may be architecture independent, it seems to be more difficult to deal with the different implementation possibilities of the IF-MGMT, partially because of the high variety of possible interference management solutions. As we have seen in Section 4, the IF-MGMT can be implemented in the WSN, in the SNET or divided between the two. The implementation of this function defines what information is given by the WSN about the spectrum usage. Again, the two extreme cases are considered: if the interference management is implemented in the WSN, the available frequencies are provided for the SNET, while if interference management is implemented in the SNET, the measured data is provided. If the IF-MGMT is implemented differently in the WSN and in the SNET, they might not be able to cooperate.

While we believe that the WSN and the SNET should freely choose which architecture and interference management options should be implemented, a set of basic requirements can be defined, to be followed by the WSN and the SNET respectively.

The basic requirements towards the WSN are as follows:

- The WSN has to follow a time slot structure where each timeslot has allocated parts for sensing, for the implementation of the CPCH, for the implementation of the CSCH, and finally for cognitive transmission. The length of the timeslot is determined by the frequency allocation scheme of the primary network, since the timeslot of cognitive transmission cannot be longer than the timeslots of the primary system. The length of the timeslot may also be limited by the primary interference constraints, since primaries that start transmitting in the middle of a WSN timeslot are not discovered until the next sensing period.
- The WSN units that implement the interface have to broadcast a pilot signal that can be heard by the SNET-Es. The time period of this signal can be longer than the frequency allocation periods (WSN timeslots), however, the longer this period is, the longer time it takes for the SNET-E to connect. The pilot signal have to contain:
 - localization information, preferable GPS coordinates, to allow the easy integration of devices with integrated GPS.
 - information on the time-slot structure of sensing, control and cognitive transmission.
- The HN has to provide spectrum availability information in a format that is useful for the secondary system and with periodicity defined by the primary system constraints.
- Optionally, the HN can provide information about the primary system(s) in the area, to ease IF-MGMT functions implemented in the SNET, like RAT parameters, transmission power, transmission radius, and interference constraints.

The basic requirements towards the SNETs are:

- The SNET has to be able to transmit on and listen to the control channels.
- The SNET has to be able to adapt to the time slot structure suggested by the WSN, and receive channel availability information and perform cognitive transmission accordingly.
- The SNET has to be able to localize itself, since this is necessary to define the target transmission area. If the SNET nodes are not equipped by GPS, the SNET has to perform localization based on the WSN pilot signals. Localization techniques are discussed in D6.2.
- The SNET has to be able to define its target transmission area to limit the information received about spectrum availability.

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9 THE SENSING AND SECONDARY NETWORK CONTROL INTERFACE: TWO CASE STUDIES

As we have shown in the previous chapters, the cognitive radio system includes the control of the sensing and the control of the secondary network. Both of these control functions can be designed based on a centralized, a cluster based or a fully distributed architecture. Below we discuss how these control functions are interfaced in the two architectures we have been developing in the project. We have focused on the cases of WSN aided cognitive radio scenario and the hybrid scenario, since in these cases the interface is between two physically distinct systems.

The two considered architectures are:

- The cluster-based WSN architecture proposed in the development of the WSN simulator and then implemented in the system level simulator.
- The centralized architecture proposed and realized in the demonstrator.

Our goal is to describe the message exchange over the SNet-E-HN interface on a high level of abstraction. The exact, more detailed description of the implementation of the Query Sessions is described in WP6 deliverable D6.3 and WP7 deliverables D7.3/D7.4, respectively on the system level simulator and the demonstrator.

9.1 CASE STUDY 1: CLUSTER-BASED OR DISTRIBUTED WSN WITH CENTRALIZED OR DECENTRALIZED SNET CONTROL

The WSN architecture and protocols proposed in WP6 spans the spectrum of the following implementations of cooperative sensing:

a) Centralized cooperative sensing

The spectrum availability information is collected at a central HN. SNet-Es contact the central HN for information about free channels. In the WSN aided scenario the HN contact information (address) can be advertised on a public page on the Internet. Below we detail the WSN-SNet QS (see section 5) for two cases of SNet architecture.

b) Cluster based cooperative sensing

In this case sensing information is collected at several HNs. Sub-cases depending on the SNet architecture follow the pattern described in the previous section, but instead of a central HN, the SNet-E (BS, SN-CH or SU) contacts the nearest HN.

It means that the respective SNet-E has to be able to find the nearest HN. The CPCH in this case uses a single hop connection. As in the centralized case, the possible HNs should issue a periodic pilot signal that defines the CPCH.

c) Distributed cooperative sensing

In this case sensing information is collected at any sensing node that is contacted by an SNet-E, that is, each sensor node can play the role of the HN. Sub-cases depending on the SNet architecture follow the pattern described in the previous sections. In this case the SNet-E has to contact the nearest sensing node. Therefore, in the WSN aided scenario each sensor node has to issue a pilot signal.

Furthermore, channel access control in the SNet can be performed following different approaches:

1. Centralized channel access control

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Sensing information is collected at the central interface WSN node, that acts as a fusion centre for the specific SNet, and the channel access within the SNet is coordinated by a central SNet-E – typically called as secondary base station (BS). This constitutes the simplest case in terms of sensing and cognitive transmission interface. Only the central HN and the central SNet-E communicate. The QS is as follows:

1. The SNet-E contacts the HN with a request message, including some representation of the area of communication and the required bandwidth.
2. The HN answers with the main rules of spectrum access (e.g., synch requirements, silent periods) and the spectrum availability map, or similar. The information given on spectrum availability depends on the implementation of the IF-MGMT function.
3. The SNet-E decides about the bands to be used and sends the list to the HN.
4. The SNet-E gets refreshed spectrum maps (or similar) from the HN, whenever the availability changes.

These messages are exchanged over the CPCH (see below). We can see two options to implement the CPCH: the SNet-E may be able to use long distance connection to the HN using the primary technology (GSM, 3GPP LTE), otherwise the CPCH uses a multihop connection through the WSN to the HN. To make the CPCH available for the SNet-E in this case some units of the WSN have to issue a periodic pilot signal. The characteristics of the pilot signal should be described on a public webpage on the Internet.

2. SNet-CH based access control

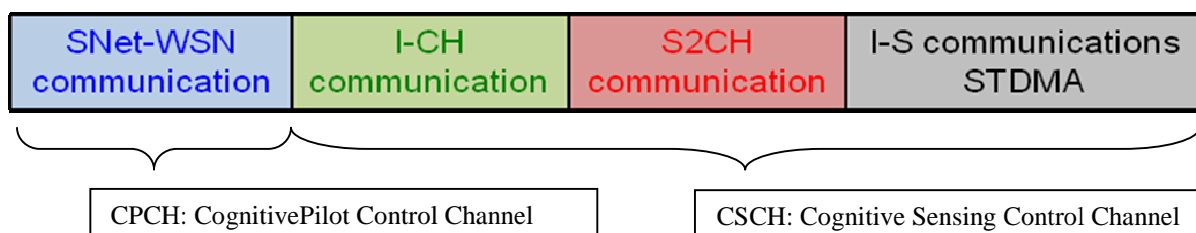
In this case sensing information is collected at the central HN (the FC) and the channel access within the SNet is coordinated by several SNet-Es, with independent interfaces towards the HN. The QS is as follows:

1. Each SNet-E with active secondary unit contacts the HN with a request message, including some representation of the area of communication and the required bandwidth.
2. The HN answers with the main rules of spectrum access (e.g., synch requirements, silent periods) and the spectrum availability map, or similar.
3. Each SNet-E decides about the bands to be used – may coordinate with other SNet-Es – and sends the list to the HN.
4. Each SNet-E gets refreshed spectrum maps (or similar), whenever the availability changes.

As we can see, the above steps from 1 to 4 are general for arbitrary SNet architecture, and therefore the interface and the related QS can support a variety of SNETs.

9.1.1 WSN time slot structure

The WSN protocols proposed in WP6 foresee a unique frequency channel for the exchange of information within the WSN. For the provision of real-time channel availability information to SNet, the physical channel is organized in time frames: each frame is roughly divided in the four following subframes, each of which has a different scope:



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Now, the first part of the frame (blue box) build up what we call the CPCH, whereas the second one (other boxes) all together form the CSCH. The structure of the latter is detailed in D6.3.

The CPCH constitutes the physical resource that implements the WSN-SNet interface. In the next subsection we detail the messages that are exchanged through this interface.

9.1.2 Message exchange over the WSN-SNet interface

In the case of cluster-based WSN architecture, the interaction among the SNet-E, which is responsible for collecting WSN responses on channel availability on the side of the SNet, and the WSN, requires the identification of a WSN entity, which is typically a CH, to which the SNet-E interfaces. Note that the SNet-E can be a central resource management unit for the SNet, i.e. a BS, in the case of centralized channel access, or a simple secondary node that will eventually transmit according to the resources provided by the WSN.

The identification of the WSN interface entity is achieved in the following way. All the WSN CH's, periodically transmit over the CPCH a beacon message, called CPS (cognitive pilot signal) that allows the secondary nodes to identify the WSN cluster in which they are located (see D6.2).

Clearly, in order to interact with the WSN on the CPCH, the SNet nodes that can have an interface role, must be endowed with the capability to transmit and receive on the CPCH frequency.

Apart from the CPS, the messages that can be transmitted on the CPCH are divided in two categories:

- a) Messages in both direction for SNet-Es to connect, authenticate, and register themselves to the WSN CH. These messages have not been implemented in the WSN simulator.
- b) Messages for the handling of the query session, in particular:
 1. RES_REQ message, from SNet-E to WSN CH,

This message contains information on the nominal interference region that would be affected by a specific secondary transmission, the one for which the query session has been started.
 2. RES_GRANT message, from WSN CH to SNet-E.

This message contains the set of frequencies that can be handled by the SNet-E: in the case of centralized access coordination, this is an aggregate information containing a set of channels that the SNet unit has to assign to STxs. In the case of CH based coordination, this is directly the channel provided by the WSN to the secondary node.

Given that a CH may be in the position to serve different SNet-Es, and the exact number of them is unpredictable, our choice has been to assume that, inside the CPCH, besides a dedicated time for beacon messages, the rest of the frame can be accessed through a random access, CSMA-like MAC.

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9.2 CASE STUDY 2: HYBRID ARCHITECTURE WITH CENTRALIZED WSN AND CENTRALIZED SNET CONTROL

9.2.1 Centralized architecture, dedicated sensor network, wired connections

The demonstration scenario #1 consists of a small number of sensor nodes, a fusion centre, and a SNet controlled by a BS. All these units are connected via wired Ethernet. In the demonstration the primary system is a WiFi network.

According to our terminology defined in the previous sections this scenario implements centralized sensing functionality, and centralized control within the SNet. The IF-MGMT is fully implemented in the WSN and provides the SNet with available frequencies. The IF-MGMT does not set a power constraint on the secondary system but instead implicitly utilizes the system peak power constraint as the limit. The HN-SNet-E interface and the QS defined in Section 5 are implemented in the FC and in the BS. The detailed message flow, including even message exchanges within the WSN and the SNet, is presented in deliverable D7.3. The implementation is detailed in D7.6.

9.2.2 Ad-hoc secondary network also performing the spectrum sensing

The demonstration scenario #2 consists of a small number secondary nodes also performing spectrum sensing and a couple of nodes performing sensing only. Cluster based and distributed control solutions are implemented.

In the cluster based architecture the secondary nodes are organized in a cluster based cognitive network, where cluster heads control the channel access. That is, this scenario implements the cluster based channel access control according to the terminology of this report, and the CHs implement the SNet-E functionality. In addition, sensing control is organized according to the same cluster based architecture, that is, the CHs implement not only the SNet-E but also the HN functionality, with internal SNet-E – HN interface. The WSN-SNet interface is thus implemented locally in the CH unit. The interface between SENSE and IF-MGMT functionality is placed between the CHs and the units performing sensing, both if they are sensor nodes or ad-hoc secondary nodes.

In the second case distributed control is implemented both for sensing and channel access. The secondary units themselves perform cooperative sensing, and each secondary unit implements the HN functionality. Channel access is controlled in a distributed way, where pairs of secondary units coordinate. Contention among secondary unit pairs is controlled by CHs. This solution is defined as hierarchical channel access coordination in Section 7.3. This means that both the SNet-COM—IF-MGMT, and the IF-MGMT – SENSE interfaces are placed within each secondary node, apart from the contention resolution within the CHs.

The detailed message flow is presented in deliverable D7.3.

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10 DISCUSSION

In this document we defined the functional units and the physical entities participating in the sensor network assisted cognitive communication system defined in the SENDORA project. Specifically, we discussed the role of the secondary communication control, the interference management and the sensing control functions and showed how these functions can be assigned to the physical entities of the wireless sensor network and of the secondary network.

We defined the logical interfaces between the functional units and the resulting physical interface between the WSN and the SNet depending on the implementation of the interference management function. In addition, we discussed how the control architecture of the WSN and the SNet, being centralized, distributed or cluster based affects the way the two networks have to be interfaced.

We concluded that the architectural options do not significantly affect the interface, or more precisely the sequence of message exchanges, what we call as query session. Instead, the various options of the implementation of the interference management in the SNet and in the WSN, and also, the variety of the possible interference management algorithms itself makes it more challenging to define a generic interface that works for arbitrary WSN and SNet.

Likewise, while the functional entities to organize sensing, interference management and secondary communication functionalities are clearly identified, different secondary and wireless sensor network architectures will position them in different physical entities, potentially in a distributed manner. This leads to different interfaces between physical entities, with various different communication requirements that must be accounted for in the system design.

Still, we argue that there is a need for a generic interface that allows the cooperation of WSNs and SNetS of different structures and under different primary systems. This approach would allow the emergence of new paradigms and network applications. We believe that the standardisation activities in the area should define general system requirements towards the sensor and secondary networks and define pilot and cognitive control channel structures that support a generic interface.

The internal subfunctionalities within the interference management functional block, and the interfaces between them are potential candidates for a first-try real life interface between a WSN and SNetS. For instance, by placing the interference estimation and frequency selection, and the support for multiple SNetS within the WSN, and leaving fine-grained resource allocation decisions to the SNet, a workable interface can be defined.