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DISSEMINATION LEVEL		
PU	Public	
PCA	Public with confidential annex	X
CO	Confidential, only for members of the consortium (including Commission Services)	

EXECUTIVE SUMMARY

This report discusses the network dimensioning and protocol design issues of cooperative spectrum sensing for supporting cognitive radio operation. Considering network dimensioning, the document describes analytic tools to express the expected sensing performance as the function of the network density and derive the necessary level of sensor cooperation for distributed sensing. Considering the wireless sensor network (WSN) protocol design, it describes the WSN protocol stack necessary to collect the sensing information from the sensors and deliver it for secondary network cognitive communication management.

The main goal of this document is to evaluate various solutions for the protocol stack design, covering centralized, distributed and clustered network architectures, and different sensing and data fusion approaches. In this document we address the different design approaches separately and discuss the advantages and disadvantages of the proposed solutions. The conclusions of this deliverable will lead our activities in the next phase of the project, when the goal is to define a cross-layer optimized protocol stack.

The document covers the two scenarios addressed in the Sendora project: the case when a fixed deployed sensor network performs spectrum sensing, and the ad-hoc case, when the secondary terminals perform spectrum sensing and share sensing information.

Specifically, the report consists of the following main parts:

- Sensor network dimensioning for reliable spectrum sensing, considering both the fixed WSN and the ad-hoc scenarios. This part mainly discusses the case when the sensors perform hard decision combining, evaluates the gains of the fixed sensor deployment and the density regions where ad-hoc networks can achieve efficient spectrum access. In addition we report the first results of the evaluation of the optimal soft-decision combining solution and show the gains of soft decision combining compared to hard decision combining.

- Sensor network protocol design, mainly focusing on the fixed WSN scenario but also addressing some aspects of the ad-hoc case. Here we discuss the traffic flows in the sensor network, present the requirements of the protocol stacks, discuss the possible selection of protocols for given network layers, considering systems with centralized control and more distributed systems based on a clustered, hierarchical network architecture. We present the first results of the cross-layer optimization efforts, specifically discussing the possibility and efficiency of jointly optimized information aggregation, routing and sensor selection.

- Finally, we present in detail the protocol stack adapted for the demonstration activities of the project. For demonstration, the Eurecom/Thales OpenAirInterface stack will be used. This stack is not optimized for the specific application of distributed spectrum sensing but allows the demonstration of sensing and cognitive capabilities in the scenarios already specified in the D7.2 deliverable. Here we describe the extensions of the available protocol stack that will be provided for the demonstrations.

In this deliverable WSN protocols are discussed and evaluated in isolation. The cross-layer optimization of the protocol stacks will be reported in deliverable D6.3, entitled “Report on cross-layer protocol stack design”.

CONTENTS

1 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

The purpose of this document is to summarize the results of the WSN dimensioning and protocol design activities performed in WP6. The results reported in this deliverable will guide the continuation of the protocol design in WP6 and will give inputs for the demonstration activities in WP7, considering both the validation trials and the simulation based evaluation.

Specifically, we specify the communication requirements in the WSN, derived from the interference constraints in the primary system and motivate the design of an original protocol stack. We then summarize our results on sensor network dimensioning, considering the requirements of reliable sensing. The output of sensor network dimensioning is the preferable sensor density, which then in turn is input for the protocol design.

Considering the protocol design, we report different approaches for efficient spectrum measurement fusion, considering the individual elements of a protocol stack. In this deliverable these protocols are discussed independently from each other, however, these evaluations should then lead to the cross-layer optimized design performed in the last part of the project. The goal of the deliverable is to collect all information that is required to start this overall system optimization.

In addition we describe the protocol stack that will be used for system demonstrations. To allow the demonstration of the validation trials defined in D7.1 and detailed in D7.2, the Eurecom OpenAirInterface protocol stack (depicted in deliverable D7.2) will be adapted and extended, in particular to play the role of WSN nodes in the validation of the WSN aided Cognitive Radio concept.

1.2 DOCUMENT VERSION SHEET

Version	Date	Description, modifications
1.0	07/07/2009	First release
2.0	28/06/2010	Second, updated version answering period 2 review comments

1.3 DOCUMENT ANNEXES

The document annexes A, B and C are confidential to the Consortium members and to the Commission Services.

2 SYSTEM DESCRIPTION AND PROTOCOL REQUIREMENTS

2.1 THE WSN AIDED COGNITIVE RADIO NETWORK

We consider the Sendora reference system defined in project deliverable 2.1 version 3.0. A cognitive network in the area of a primary network operation would like to use the spectrum left unused by the primary system. It is allowed to do that if it can ensure that the quality of service degradation in the primary system will be limited. To achieve this, the cognitive network aims at controlling its transmission characteristics, for example, used bandwidth and transmission power. This cognitive control is based on spectrum availability information collected from the area where the secondary transmission could cause interference. The spectrum availability information is provided by spectrum sensors. The spectrum sensors may be deployed for this specific reason and then they form a fixed wireless sensor network (WSN), or can be implemented in the secondary units, in this case they form an ad-hoc network. In both cases the cooperative decision of a set of sensors is required for reliable spectrum sensing, and therefore two issues have to be addressed: what is the necessary density of the sensor network to achieve reliable sensing, and what protocol design fits this specific task.

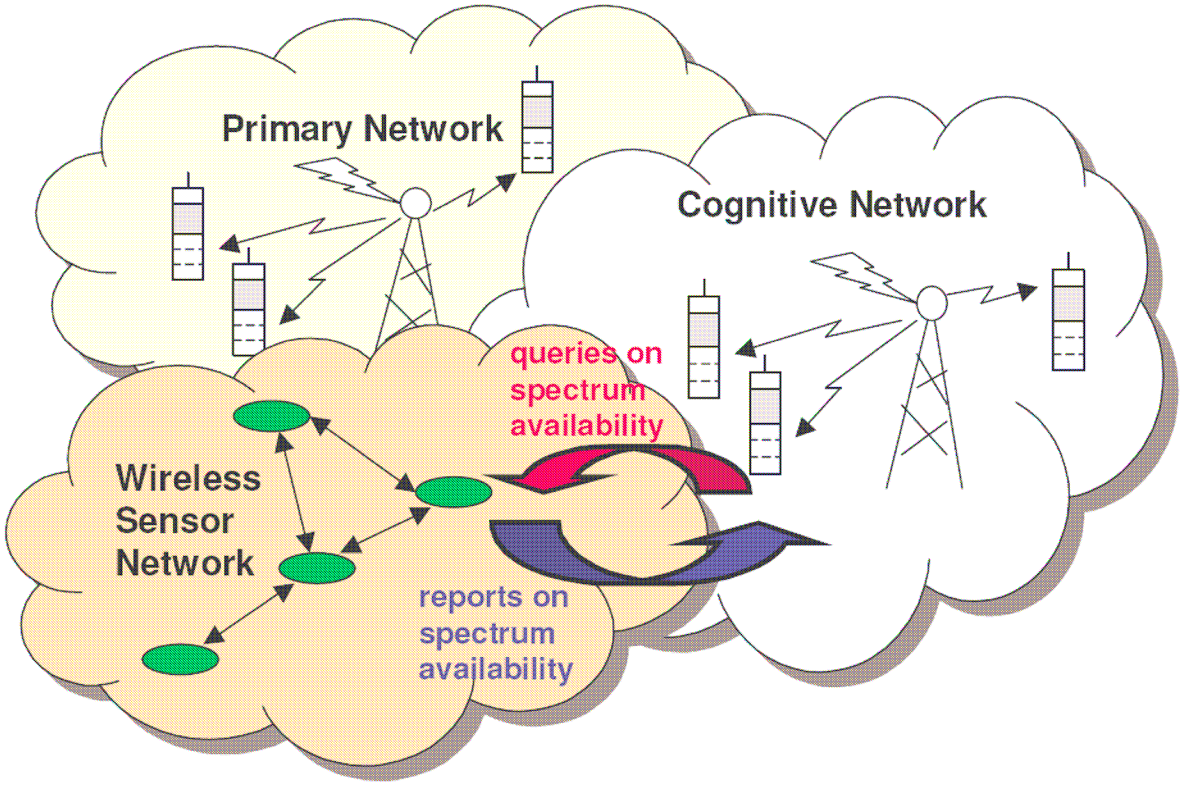

Figure 1: Wireless sensor network aided cognitive radio

2.2 SYSTEM REQUIREMENTS

The communication protocol design is driven by the requirements of the application, that is, the cooperative spectrum sensing that will support the cognitive operation in the secondary networks. Therefore, to define the quality of service requirements in the fixed or ad-hoc wireless sensor networks we have to start with the requirements of the primary technologies.

Project deliverable D2.1 summarizes these quality constraints for possible primary technologies, including WiFi wireless LANs, UMTS/HSPA cellular mobile networks, LTE based cellular mobile networks and digital television. The quality constraints include maximum response time, maximum outage probability, acceptable level of interference, maximum transmission power, signal bandwidth and signal detection threshold.

These constraints are to be considered by different cognitive radio functionalities such as sensing, interference management and information transmission – that is, protocol design. Specifically:

- Maximum response time: limits the time available for sensing, the fusion of sensing information and the transmission of sensing control information.
- Detection threshold and transmission power: together defines the communication radius of the primary system and directly controls the interference management functionality. It also defines the area of possible interference and therefore the area of sensing information fusion. This in turn affects the communication protocol design.
- Acceptable level of interference: affects the interference management, but also the granularity of the sensing information the wireless sensor network has to collect – that is, the network load.
- Outage probability: limits the response time and the probability of interference over the acceptable level. Affects the performance requirement of sensing in terms of accuracy and sensing time, and the communication protocols, through response time. Affects also the interference control – since only scheduled transmissions can cause outage even if some primary signals have not been detected.

Based on the above constraints we can define performance measures for network dimensioning and protocol design. The performance measures that directly affect the primary performance is *interference probability* and *response time*. The interference probability depends on the signal *missed detection probability*, and on the *secondary network load*, while the response time depends on the *communication and sensing delays*. The missed detection probability depends on the *granularity of the collected information*. Communication delays depend on the communication patterns and protocol stacks and on the amount of information to be collected from each sensor, that is, on the information granularity. More data to transmit usually means larger delays in the considered limited bandwidth scenario.

From the secondary network point of view the performance measure is the utilization of the free frequency resources. This depends on the sensing time – the secondary users are not allowed to transmit during spectrum sensing, and on the communication delays, since no secondary users are allowed to transmit until a decision is made, and on the *probability of false alarm*, that is, on the probability that a channel is detected occupied, while it is actually free. Again the false alarm probability is a function of the sensing time and the information granularity.

Finally, the goal of the communication protocol design is to maximize the utilization of the secondary network, given that primary system constraints hold.

The first question we have to investigate is whether existing communication protocol stacks well suit our scenario. In that case all we need is to design the application protocol, that is, the message exchanges:
- between the secondary units and the WSN for the cognitive control,
- and within the WSN for cooperative sensing.

2.3 COMMUNICATION PATTERNS AND PROTOCOL OBJECTIVES

The protocol objectives are directly related to the communication needs of the application. In our case the application is the sensing information fusion to assist cognitive radio operation. Therefore the application consists of information exchange between the secondary units and the sensor network to request and assign available frequencies and within the sensor network to define the set of available frequencies.

Reactive and proactive communication

We use the term reactive sensing if these two communication flows are coordinated and the terms proactive sensing if they are not coordinated, but the collection of sensed information runs independently from the secondary requests. Both will be considered in the protocol design reported in Section 4.

Centralized and decentralized sensing

We can talk about centralized and decentralized sensing depending on the existence of a central unit that collects spectrum measurements and assigns frequencies to use in the cognitive network. We use the term *fusion centre* for this central unit. If spectrum sensing is performed by the secondary units the cluster head of the secondary network acts as fusion centre for that ad-hoc network. Then an upper level entity might be necessary to coordinate and validate the frequency assignments done by the cluster heads.

In a fully decentralized solution the secondary unit asks the nearby sensor for free frequencies (or collects all necessary information itself in the case of the ad-hoc scenario). In the middle we can define clustered solutions where information is fused locally and exchanged among these units.

Information exchange between the secondary units and the sensor network

The information exchange between the secondary units and the sensor network is defined by WP4 in deliverable D4.2. The information flow graphs were also reported in D7.2 at the description of the demonstration scenario.
Figure 2 repeats some of the scenarios to ease the understanding. The above figures do not show the information exchange within the WSN, that is, all the messages that are necessary to provide frequency availability information to the fusion centre (FC).

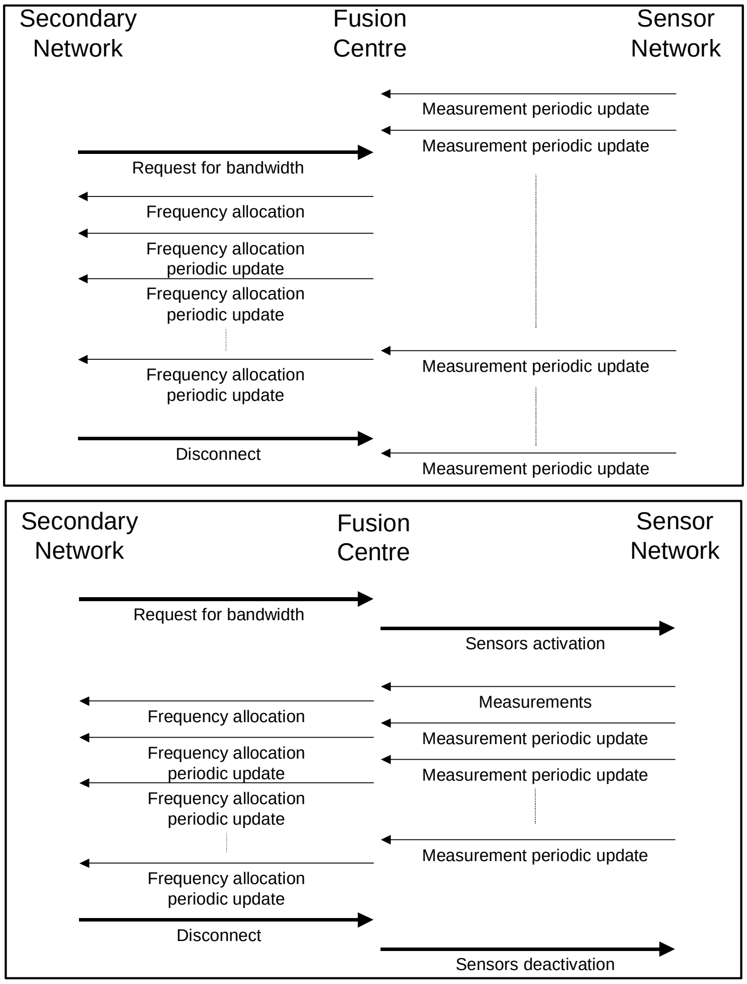

Figure 2: Centralized control with proactive and reactive sensing

Characterization of protocol requirements

The main goal of our protocol design work is to define the optimal communication patterns that fulfil the requirements of the application.

Let us collect the main characteristics of the distributed sensing application:
- Amount of information to be transmitted: sensors in the area of possible interference have to report spectrum availability information periodically, and over a larger set of frequencies. That can mean a couple of bytes even in every 10ms per sensor. The amount of raw data to be transmitted is rather high, at least compared to the estimated available transmission rate of the shared medium which is in the range of 10kbps.
- Transmission delay: the delay of information fusion and the transmission of control information to the secondary unit should be in the ms range to fulfil the response time constraints of the primary units and still achieve an acceptable level of cognitive network utilization.
- Information locality: there are two levels of locality in the considered system. For distributed sensing, measurements of nearby sensors have to be considered, while for cognitive actuation, distributed decisions from the possible interference region has to be taken into account.
- Measurement correlation: measurement information of nearby sensors is expected to be correlated.

- Spectrum sensing itself consumes significant energy, and as a consequence, the energy consumption of transmission protocols is not considered as a priority, even if it shall be optimised when possible.
- Spectrum sensing over a large set of frequencies is a complicated tasks and spectrum sensors are expected to be expensive.

Considering the above characteristics we can conclude that our application is:

- not a typical wireless mesh application (WiMax), which is optimized to carry point-to-point transmissions;
- not a typical personal area network, like Bluetooth, since transmission distances are higher.

Our scenario is closest to a sensor network application, as a large number of nodes cooperate to perform a given task. However, it is not like the typical sensor network applications considered in the literature and for standardisation activities (IEEE 802.15.4 and Zigbee). First of all, transmission energy is not a main issue, since sensing consumes high amount of energy anyway. Therefore, the sensor nodes do not need to follow a sleep/awake schedule. Then, a dedicated, though low bitrate channel will be used for information fusion, and not the ISM band, which changes the required physical layer functionalities. Finally, since the delay requirements are low and the expected data traffic is high, medium access control and routing have to be optimized for the exact traffic pattern in the network.

Therefore we claim that the design of a dedicated protocol is necessary to satisfy the needs of the spectrum sensing application. The protocol should be able to fuse periodically generated messages with low transmission delays. To relax the high requirements on the protocol, we can take into account that *i)* the measurement data has localized importance and *ii)* nearby measurements can be correlated due to the features of the measured phenomena (radio signal). Therefore, by clever protocol design we can achieve that only information that is significant for the cognitive operation is fused, decreasing in this way the required transmission rates.

3 WSN DIMENSIONING FOR SPECTRUM SENSING

In this section we summarize our results on sensor network dimensioning for sensing quality. Considering the fixed sensor network that is deployed to assist the cognitive operation we derive the required network density and the optimal level of sensor cooperation for distributed sensing. Considering the ad-hoc network scenario where the secondary users themselves perform the spectrum sensing and share this information with each other we evaluate the sensing performance with respect to the secondary user density and the effect of sensing failures considering the caused interference and the capacity available for the secondary users. Finally we report some results on distributed sensing with optimal soft information combining.

We will return to the problem of network dimensioning in the last period of the project. Using the mathematical framework already defined we will incorporate the results of the project on advanced spectrum sensing techniques and perform the network dimensioning exercise to consider even the communication needs, which in turn depend on the protocol stack.

Previous work in the area of distributed sensing for cognitive operation has mainly been focusing on the problem of cooperative detection of a single, high power primary source, like Digital TV broadcasters. Authors in [1] analyze how cooperative sensing of TV signals reduces the requirements for single sensors in terms of channel detection times and reliability of observations. In [2] and [3] it is concluded that cooperative sensing can provide high reliability spectrum measurements in fading environments, where single sensor performance is not acceptable. In [3] a trade-off between the level of sensor cooperation and delay overhead is also studied. The signal detection in these papers is based on energy detection schemes though lately more sophisticated techniques are introduced as well [4]. Experimental results for single and cooperative sensing with energy detection are presented in [5]. Authors in [6] study the performance of cooperative sensing under hard decision combining and OR and AND decision rules, while [7] extends the study to include log-likelihood ratios and weighted hard combining. A scenario similar to the one in our work is considered in [8], as it addresses the case when the secondary system operates on the same spatial scale as the primary one. It assumes collaboration among the secondary nodes and investigates the node density required for reliable signal detection. Based on channel budget calculations it concludes that an unrealistically high density of active secondary users is necessary under realistic values of signal attenuation. Interference modelling in cognitive networks is addressed in [9] and [10]. The authors of [9] propose a way to model the interference between the primary and cognitive network, where the interference originates from imperfect spectrum sensing. They investigate the trade-off between the capacity of the cognitive network and the interference caused to coexisting primary users. The paper assumes that a missed detection always results in interference and does not consider the interference between the primary and secondary users as distance-dependent. A recent interference modelling approach that takes the spatial distribution of the cognitive users into consideration is proposed in [10], where the authors model the accumulative interference to a primary user in the case of multiple simultaneous cognitive user transmissions.

3.1 WSN DIMENSIONING FOR THE CASE OF FIXED DEPLOYED SENSOR NETWORK AND HARD DECISION COMBINING

First we give an overview on the fixed WSN dimensioning problem. The detailed description of the mathematical model and extensive set of numerical results are available in [11].

Scenario description

The addressed scenario is depicted on Figure 1. The primary and secondary systems – base stations as well as end users - are located in the same geographical area. The wireless sensor network (WSN) that implements the spectrum sensing process is deployed deterministically according to a regular pattern. Specifically, we examine the triangular and square patters. The density of the network is characterized by the distance between two arbitrary adjacent sensors (minimum distance). For simplicity we consider only the sensing on a single frequency band.

The cognitive actuation process is as follows. Sensors are actively sensing the frequency band according to a slotted schedule. Each time-slot starts with a measurement period. Once the local measurements are taken, the information is transmitted to a central network entity, called fusion centre. By combining received local information according to the cooperative sensing rules, the fusion centre updates spectrum occupancy map consisting of the possible locations of active primary transmitters. A spectrum map corresponds to a particular frequency band; a complete spectrum occupancy map consists of a set of parallel maps associated with each band that is available for dynamic spectrum access.

Secondary units wishing to communicate in the considered area first request available frequency bands from the fusion centre. Based on the frequency maps, and possibly knowing or estimating some other system parameters, like primary transmission power and channel gain, the fusion centre allocates frequencies and transmission powers for secondary users such that the interference at the primary receiver will be kept below the value specified for the given primary system technology. These frequency and power allocations are valid for one time-slot and are refreshed periodically. The period of the updates is defined by the primary system interference constraints. Since primary transmissions are not synchronized with the secondary ones, when a primary node starts to transmit, its transmission may interfere with a secondary transmission correctly scheduled for that period.

We assume that the WSN can use a narrow licensed frequency band to set up a common control channel (CCC) for communication among the sensor nodes, as specified in deliverable D2.1. All communication from and to the secondary unit, the fusion centre, and the sensors use this band. We recall that the reason for choosing a licensed band is to ensure the reliable and fast transmission of sensing information.

In this report we assume that sensors perform energy detection. Each sensor makes a "yes" or "no" (binary) decision about the existence of the signal based on the energy collected during the measurement period. Cooperative decision is made by combining these decisions. Sensor cooperation is implemented based on the general *k-out-of-n* rule, implying that for a positive conclusion regarding spectrum occupancy at least *k* out of a total of *n* collaborating sensors must provide positive local decisions. AND and OR decision policies are special cases of the general *k*-out-of-*n* rule. The *k*-out-of-*n* rule in our case is implemented in the fusion centre. The fusion centre considers all groups of *n* collaborating sensors and derives a collaboratoive decision for each of these group of nodes. The outcomes of all these decisions constitute the spectrum occupancy map.

Cooperative sensing and level of cooperation

Because of signal attenuation due to path-loss the received signal power collected at an energy detector decreases as the distance between the sensing device and the primary transmitter increases. In addition, due to multi-path fading and shadowing phenomena the stochastic properties of the received signal power make it harder to distinguish from background noise power. For a given energy threshold the probability of detection can therefore be described as a decreasing function of spatial distance and noise and fading variances. This implies that a sensor can significantly contribute to the cooperative decision only if its distance from the primary transmitter is low. At the same time the diversity gain of cooperative sensing decreases if sensing nodes are very close to each other and their measurements become correlated.

To reflect the dependency on the distance of the primary transmitter and the sensing nodes we define the set of sensors that are in the same distance from a point in space as *tiers*. For example, if the sensor network forms a triangular grid, we pick the centre of a triangle, and define the tiers around it. As shown on Figure 3 there will be three sensors in the first tier, three in the second, six in the third, etc.

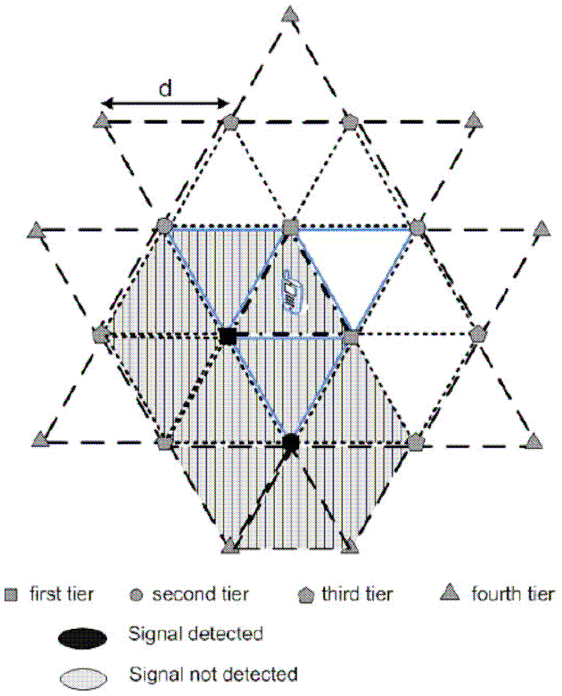

Figure 3: Sensor tiers of cooperative sensing

System model

We consider the pair of basic performance metrics to evaluate the detection performance of the wireless sensor network. The probability of missed detection expresses the probability that an active primary user could not be detected by the sensor network within a sensing interval. The probability of false alarm defines the probability that while no primary transmitter is active the system makes a positive decision. These metrics, as functions of the particular system design principles and parameters, like decision rules, network density or signal detection times, provide quantitative results on the interference on the primary system and the throughput of the secondary system.

The probability of false alarm at an arbitrary sensor depends on the selected detection time as well as on its radio environment in the absence of primary signals, i.e. the noise power. The probability of missed detection, however, depends on the location of the primary transmitter as well. Since the sensing performance of the WSN depends on the primary transmitter location, we could consider the average sensing performance, or the worst case sensing performance, or even some more detailed statistics. Since interference limits have to be hold even when the primary transmitter stays in an unfortunate physical location, we decide to model and evaluate the worst case sensing performance, that is, when the location dependent missed detection probability is the highest.

We consider OR decision rule for the cooperative decision. In this case the missed detection probability is the highest when the distances between the primary transmitter and the sensors of a tier are jointly maximized. This is the case when the hypothetical primary user lies at the centre of the first-tier-triangle.

Sensing performance based on energy detection is extensively studied in the literature. In our proposed scheme the sensors are sampling within a band of interest for a given sensing period. Energy estimation is formed by squaring and integrating the received samples within this time period. The measurement is compared to a pre-selected energy threshold and a hard (binary) decision is formed. Increasing the decision threshold increases the missed detection probability and decreases the false alarm probability, while decreasing the decision threshold has opposite effects.

A simple power model is considered to model the signal propagation at the radio link between a primary transmitter and a sensor. We also consider small-scale Rayleigh fading as well as log-normal shadowing for the received signals at the sensing nodes. Additive white Gaussian noise is considered to account for the background noise at the receiver. Considering fixed or slowly moving users for the primary network, and allowing other objects, i.e. possible scatterers, to move at a speed of up to 10 m/s, the channel coherence time is in the order of 5 ms. Therefore within a sensing interval we can consider the channel as slowly fading, which means that for a sensing interval we can assume the same fading gain.

The correlation distance of the small scale fading is in the order of tens of wavelengths. For carrier frequencies around 2GHz the wavelengths are in the order of 15 cm. The correlation distance of the shadowing attenuation depends on the considered propagation scenario. For urban or dense-urban scenarios the correlation distance of the shadowing effects is in the range of 5 and 50 meters. For simplicity we assume that minimum sensor distances are larger than 50 meters, which means that sensor observations can be considered independent. We will evaluate this assumption based on the numerical results.

Numerical results

Now we give some representative numerical results on the probabilities of false alarm and missed detection with respect to WSN density and for different levels of sensor cooperation (corresponding to different numbers of participating tiers). We consider OR decision rules and worst case performance for missed detection probability. The evaluation is conducted based on two different primary technologies: WLANs and 3GPP Long Term Evolution cellular systems. Both systems employ OFDM modulation with, however, different transmission power, coverage ranges, operating frequencies and interference constraints.

Table 1 lists the parameter setup for the performance evaluation. Two different sets of parameters are to be used for the two different case studies. The width of the sensing band is set to 200kHz, to allow for cognitive operation within OFDM sub-bands.

Case Study	WLAN	3GPP LTE
Signal Bandwidth	20MHz (all channels)	5MHz
Signal Power	15dBm	24dBm
Path Loss	4.5	4
Shadowing (mean, variance)	0dBm, 10dB	0dBm,5dB
AWGN Power	-96dBm	-96dBm
Mis. Detection Probability	10^{-3}	10^{-6}
Sensing Time	0.25msec	50μsec
Sensed Band Size	200kHz	200kHz
Signal Power in Sensed Band	-5dBm	4dBm

Table 1: List of parameters in the considered case studies

We start to evaluate the performance of sensing cooperation by evaluating the missed detection probability and false alarm probability tradeoff as the function of the sensor cooperation. While, as discussed in D7.2, the limit on the missed detection probability is given by regulations, the investigation of the tradeoff is necessary to see the cost of the strict interference limits.

Figure 4 presents the results for the first case study where the primary technology is an 802.11x WLAN. First it shows the worst case missed detection and false alarm probability pairs for 55m sensor distance. On one curve, the missed detection and false alarm probability values are tuned by changing the detection threshold value at the single sensors. As the figure shows, the detection performance improves with the number of cooperating sensor tiers, up to a certain point, where no further improvement is possible with increasing the number of cooperating sensors. Increasing the number of sensor tiers that contribute to the decision process decreases the missed detection probability, since more information is aggregated into the cooperative decision. The reliability of the added information, however, decreases with the distance from the primary transmitter. At the same time, keeping the decision threshold constant, the probability of false alarm increases continuously as more and more sensors are added to perform the cooperative decision. Therefore, there is an optimum of the number of sensor tiers that should be included in the decision process. In Figure 4.a five tiers achieve the best performance for all considered decision threshold level.

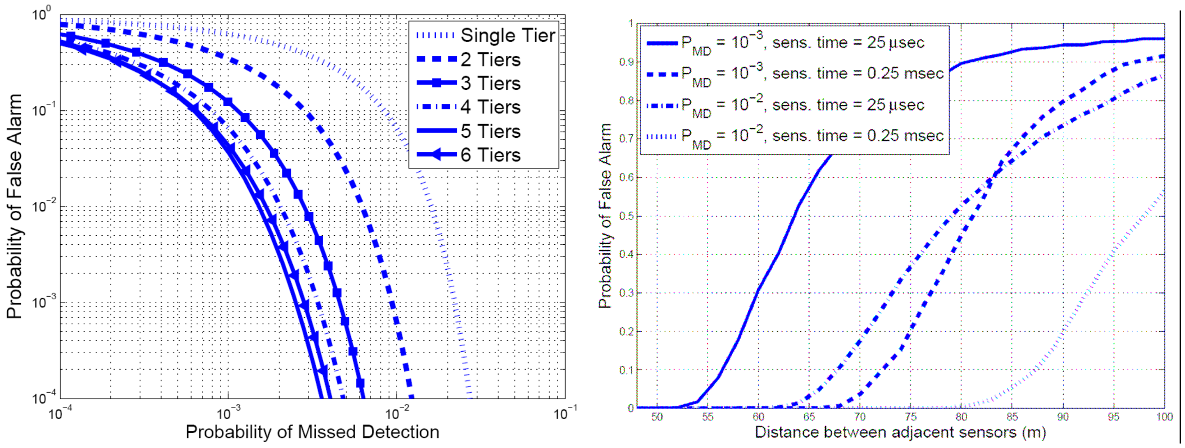

Figure 4: a) Sensing performance for various levels of cooperation and b) false alarm probability as a function of network density. WLAN case study.

In the following we keep the missed detection probability constant – since that is controlled by primary system regulations – and evaluate how the false alarm probability depends on the sensing time and the WSN density. In Figure 4.b we compare the probability of false alarm with respect to network density for different missed detection probabilities and channel detection times. The inter sensor distance needs to be around 50 meters to keep the probability of false alarm around 1-5%. This density should be feasible for WLAN primary systems.

Figure 5 depicts the numerical results for the LTE case study. The detection of LTE signals could be considered to be an easier task, compared to the WLAN case scenario, due to higher transmission powers of primary signals. The more strict detection constraints, however, as well as a difference in missed detection probability constraint of about 3 orders of magnitude result in a quite similar required sensor network density. A larger inter-sensor distance is allowed but it is clearly of the same order of magnitude. Since this density seems to be quite high, as future work we will investigate ways of decreasing this density requirement, by more sophisticated sensing solutions or by substituting the hard decision combining with optimised soft decision combining for distributed spectrum sensing.

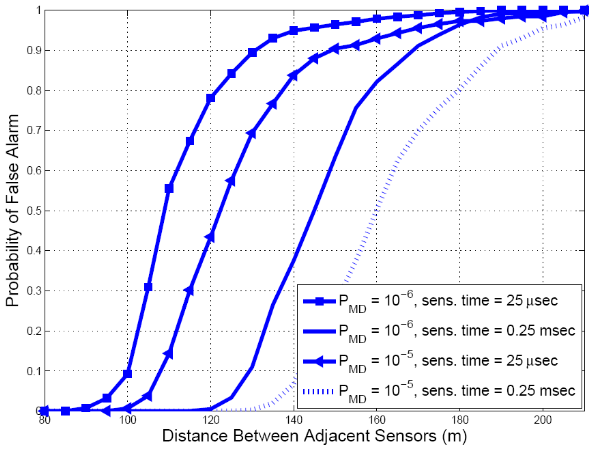

Figure 5: Probability of false alarm as a function of network density. LTE case study.

Finally, we conclude that our assumption that shadowing does not introduce correlation among the observations of the nearby sensors holds, since the minimum sensor distance is over 50m in both scenarios.

Above we investigated the WSN density requirements considering the sensing performance measures probability of false alarm and probability of missed detection. Note however, that other performance requirements may necessitate higher densities. First, the way distributed sensing is performed also affects the accuracy of primary transmitter localization. By increasing the number of cooperating tiers, the spatial accuracy of the transmitter localization decreases, which may lead to lower spatial frequency reuse. (E.g., on Figure 3, and considering single tier cooperation and OR decision, the primary transmitter can be anywhere in the shaded area.) To keep the detection performance at high spatial granularity, the density of the sensor network may have to be increased. Second, since the bandwidth of the common control channel is fixed, higher network density may be required to achieve the transmission rates required for spectrum measurement fusion. Network nodes in this case may be of different types: some of them performing spectrum sensing, others only forwarding measurement information.

On the other side, lower sensor density can be hopefully achieved by advanced sensing solutions and sensor cooperation based on soft decision combining.

3.2 WSN DIMENSIONING IN THE AD-HOC SENSOR NETWORK CASE WITH HARD DECISION COMBINING

Now let us consider the case when the secondary users themselves perform the spectrum sensing and share this information with each other to improve sensing quality by cooperative sensing. Clearly, the random location of the secondary users will make the cooperative sensing less reliable – even when there are many secondary users in the area their uneven positions may lead to low sensing quality in some areas. For the same reason some of the measurements may be correlated, decreasing the efficiency of distributed sensing this way. Our goal is to express this decreased efficiency compared to the fixed WSN case by comparing achievable false alarm and missed detection probabilities under similar network densities.

In this ad-hoc scenario however, low secondary user density means low secondary load as well, that is, when there are very few users in the area their sensing may be of low quality, but they will use only a small part of the bandwidth that is detected free – therefore, the interference caused to the secondary system will not be necessarily high. We investigate the interference – secondary user density trade-off by adopting a simple interference and cognitive actuation model and by optimizing the system parameters to achieve maximum cognitive capacity under limited interference probability.

The detailed scenario description, the evaluation of sensing performance in the ad-hoc case and the evaluation of achievable cognitive capacity in the ad-hoc network is presented in the confidential Annex A.

3.3 WSN DIMENSIONING WITH SOFT COMBINING DECISION

The soft combining technique, in contrast to its hard counterpart, takes measurements from several nodes, combines them, and then takes a decision on the resulting combination. As we have seen, the hard decision method takes decisions locally and then the local decisions are combined to give a global and final decision. Given that Y_i represents the local aggregate at the i^{th} sensor, a hard decision strategy would directly compare the latter to a threshold λ_i and accordingly decide whether the band is occupied or not. Soft combining, however, aggregates measurements themselves from several sensor nodes through a centralized [19] or a distributed approach [20]. Since the information loss is less in this case, a better global decision can be achieved.

The literature suggests the log likelihood ratio test (LLR) as an optimal decision rule [21]. However, the complexity in globally attaining the LLR in a centralized algorithm is substantial [22], thus distributed methods are more desirable. However, distributed solutions generally require global information which is usually attainable through gossiping. One case for example is SNR gossiping [24]. Another approach is represented in [19], that does not depend on likelihood ratios, but derives optimal linear weights through setting a centralized convex optimization problem which we denote as Linear-Combination (LC) based approach. Furthermore, another centralized approach in [24] derives closed-form weighting factors as function of the local SNR values.

In this work, we consider the problem of weighting several measurements so as to get the best possible decision about occupancy. The information is weighted and forwarded through the next hop. The final decision is taken when the aggregate is compared against the global threshold λ_{FC} at the FC. In Figure 6, we show how several measurements are iteratively aggregated.

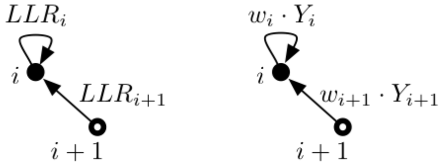

Figure 6: Incremental soft decision combining strategies, left LLR-based and right LC-based

This is also represented in the following equations:

$$A = \begin{cases} \sum_{i=1}^{N} LLR_i & : \text{LLR-based} \\ \sum_{i=1}^{N} w_i \cdot Y_i & : \text{LC-based} \end{cases}$$

where ω_i is the optimal weighting factor at each node *i* and A is the current aggregate.

The details of the work are elaborated in Annex B.

The future work on dimensioning includes a study on the sensing performance with optimal soft decision combining with respect to WSN density for the cases of fixed and randomly deployed networks. Moreover, we will also evaluate thoroughly the performance based on the latter methodology but taking into account the quantization of samples, and benchmarking it against hard decision combining. We will take into account several issues: (a) sampling time, (b) level quantization, which implies different levels of transmission power budgets (c) detection probability, (d) false-alarm probability, and (e) different combination strategies.

4 PROTOCOL DESIGN

4.1 WIRELESS SENSOR NETWORK ARCHITECTURE

In this section we identify several possible choices for the sensor network architecture and the consequent protocol stack design. The choice of a specific architecture among the ones described here, is heavily dependent on the characteristics of primary and secondary networks, in particular on relative sizes of the area of service of the networks and the coverage radius of the transmitters. Since the SENDORA project is not targeted at a specific type of secondary network, we choose to investigate different architectures suitable for different scenarios.

In the following, we consider a fixed wireless sensor network. Part of our discussion and results, however, can be extended to the ad-hoc nomadic scenario, as long as the network topology does not change quite often. The main differences between the ad-hoc case and the WSN case reside in all the issues related to energy consumption, in a lower control over the sensing granularity, and the need for sensor localization and topology control.

We first study the system wide behavior to identify the sensor network functionalities and communication patterns. We will then discuss different protocol stack alternatives for the different scenarios.

In a WSN aided Cognitive Radio scenario, the goal of the sensor network is to deliver to the secondary network suitable information on frequencies available for transmission. This information, in turn, is obtained through the elaboration, on behalf of the sensor network, of data coming from the sensors about the spectrum occupancy from the primary, licensed, network(s) in the frequency, time, and space domains. Before describing the sensor network architectures we will consider, let us make some remarks on important factors that have an impact on the sensor network design.

As said in Section 2, the system response time is a crucial system parameter, i.e. it is important that the information delivered to the secondary network is not outdated. Needless to say, the sensor network architecture has a strong impact on the system response time: the flow of information inside the sensor network, from the sensors to the entity in charge of the decision on the frequency assignment, introduces an inevitable delay. Interestingly, there are **two fundamental parameters of the secondary network** that affect the entity of this delay, and hence can drive towards a specific choice of the sensor network architecture. The first one is the transmission range of secondary users, i.e. their transmit power, the second is the size of the area of the cognitive operation, i.e. the area over which the sensor network offers its service to one, or more, secondary networks.

The **transmission range of secondary users** impacts on the delay because it determines the size of the possible interference region of secondary users, hence the number of sensors involved in the decision process: a higher number of sensors, for a constrained WSN system bandwidth, means a higher delay in delivering local information to the entity in charge of fusing the data. The **size of the service area of the secondary network** impacts on the delay because in an extended region it may happen that the entity in charge of processing the sensors data is located far from the secondary user which is the destination of the decision, in which case the message should be routed to the destination through a multi-hop pattern, thus increasing delay.

We will consider two different network configurations, centralized and clustered. In the centralized case centralized a single, network wide fusion centre (FC) controls the sensor network, collects measurements and interacts with secondary users. In the clustered case the sensors network is divided into clusters and each controlled by a local fusion centre named cluster head (CH). Each CH controls the sensing of the local sensors and is responsible of frequency assignment within the cluster. The first solution can be seen as a good candidate either when the service area of the secondary network is small and each secondary user can be reached by the FC with one or few hops, or when the delay requirements are not so strict. The clustered architecture is instead preferable when the secondary network operates over an extended area and the delay requirements are more stringent.

In each configuration we can consider a proactive version, whereby sensing is run periodically by all nodes in the networks and a reactive version whereby sensing is run on demand when secondary users ask for frequency in a given area.

Centralized Solution – Fusion Centre

In these scenarios the fusion centre collects the sensing information from the sensors. SUs interact with the fusion centre for frequency requests.

Proactive Case

In the proactive case sensing is carried out periodically by all sensors in the network. The sensing decisions are periodically diffused to the fusion centre which, as a consequence, has a complete frequency availability map of the area. The SUs entering the sensing area contact the fusion centre and ask for available frequency in their transmission region. The fusion centre assigns to the SUs available frequencies according to some criteria. The frequencies assigned to the SUs are updated over time. Updates may occur on a periodic bases or being dictated either by primary users activity which may occupy frequency assigned to the SUs or, by SUs movement to another region in the area.

Reactive Case

In the reactive case sensors do not sense the surrounding spectrum unless so required by the fusion centre. The SUs entering the sensing area contact the fusion centre and ask for available frequency in their region. In response to this request, the fusion centre activates sensors. The sensors which are activated are those which cover the area of potential SU transmission. As sensors send their measurements, the fusion centre determines a suitable frequency/bandwidth which is assigned to the requesting SU. The frequency assignments are updated over time to reflect time varying condition either in the primary and /or secondary user activities.

Clustered Solution – Cluster Heads

In these scenarios the area is divided in clusters. In each cluster a node takes the role of Cluster Head (CH) and acts a local fusion centre. A global fusion centre may still be present with the role of collecting and storing spectrum information from the CH over time but with no active role with respect to sensor activation and frequency assignment.

CHs make the frequency assignments for the SUs that are located in their clusters. It is worth pointing out that the clustered solution gives rise to the problem of distributed channel assignment, i.e. it should be avoided that the same channel is allocated to SUs in nearby cluster that can interfere with the respective receivers. This contention might be solved on the cognitive control level, that is, letting CHs exchange spectrum availability and assignment information, or within the medium access control of the secondary network.

As it will be clear in the section devoted to the description of the protocol stack functionalities, in the clustered network configuration there may be *three* different behaviors of sensors and cluster heads to sense the spectrum, collect and process the data to deliver the desired information to the secondary users:

Proactive behavior

In the proactive case sensing is carried out periodically by all sensors in the network, possibly employing a cooperative sensing algorithm at the local level. The sensing decisions are periodically diffused to the CHs which have complete frequency availability map of the associated cluster. CHs may also exchange their frequency availability map with neighboring CHs. A SU entering the sensing area contacts the closest CH, i.e., the CH of the cluster the SU is in. The CH cooperates with the CHs whose cluster overlaps with the SU transmission range, collects the information from those cluster heads and combines with its own data to provide a complete map and responds to the SU.

Hybrid proactive-reactive behavior

In the hybrid case, the low level sensing operations, in particular those related to cooperative sensing are performed in a proactive way. In other words, each sensor interacts with its neighbors continuously, to achieve better performance of its spectrum occupancy estimation/decision capability, but keeps the result of this collaboration stored locally. When a CH receives a request for bandwidth from a secondary network or from another CH, it collects the sensing information locally stored at the sensors from of its cluster. Sensors then send the updates of the sensing information periodically during the time of secondary activity.

Reactive behavior

In the reactive case sensors do not sense the surrounding spectrum unless so required by the cluster heads. The SUs entering the sensing area contact the closest CH and ask for available frequency in their region. In response to this request, the CH activates sensors in its cluster and contacts the nearby CH whose cluster overlaps with the SU transmission range, which will themselves activate their sensor as needed. Each sensor collects information from its neighbors and performs a cooperative sensing. The CH collects the results of cooperative sensing from the sensors in the cluster and from the nearby CHs to provide a complete map and responds to the SU. The frequency assignments are updated over time to reflect time varying conditions either in the primary and /or secondary users activities.

From the above description we can recognize that all scenarios are characterized by the same functionalities and communication patterns, as we summarize below:

1. Secondary users contact the closest CH or the fusion centre asking for an available frequency. The CH (or fusion centre) sends a response.
2. Sensors sense and generate local estimates. They may exchange information with nearby nodes to perform cooperative sensing estimation/decision.
3. Estimates/decisions are transmitted from the sensors to the respective CH or to the fusion centre.
4. CHs communicate with nearby CHs to request/respond cluster frequency availability maps.

We detail each of these functionalities in the next sections.

4.2 SYSTEM FUNCTIONALITIES

In the following, we give a brief description of the main functionalities of all the entities involved in the process of obtaining one, or a set of available frequency bands for secondary users to transmit. This description is general in the sense that it fits to all the considered network configurations, either **centralized or clustered, and proactive or reactive**. The key players in the process are: the secondary unit that makes the request for channel availability, the sensor nodes and the WSN entities responsible for data fusion and transmission, i.e. the cluster heads (CHs) or the fusion centre (FC).
Figure 7 gives a sketch of the involved entities; the figure refers to the clustered architecture but would apply to the centralized case with minor modification. In the figure, the secondary unit is the white box, at the centre of a circular region that indicates the interference region. The red octagone is the WSN unit responsible of the final data fusion (either FC or CH) and that interfaces with the secondary unit. The blue circles are the sensors, and the figure shows the local interaction which is performed in a distributed way to refine the spectrum estimates/decisions. The figure shows a set of sensors performing locally distributed sensing at the border of the clusters: this anticipates, as we will describe later, that at this level the clusters don't play a role. This is to ensure that even the sensors at the border of each cluster can benefit from the whole cooperation of nearby nodes, even those located in a different neighboring cluster.

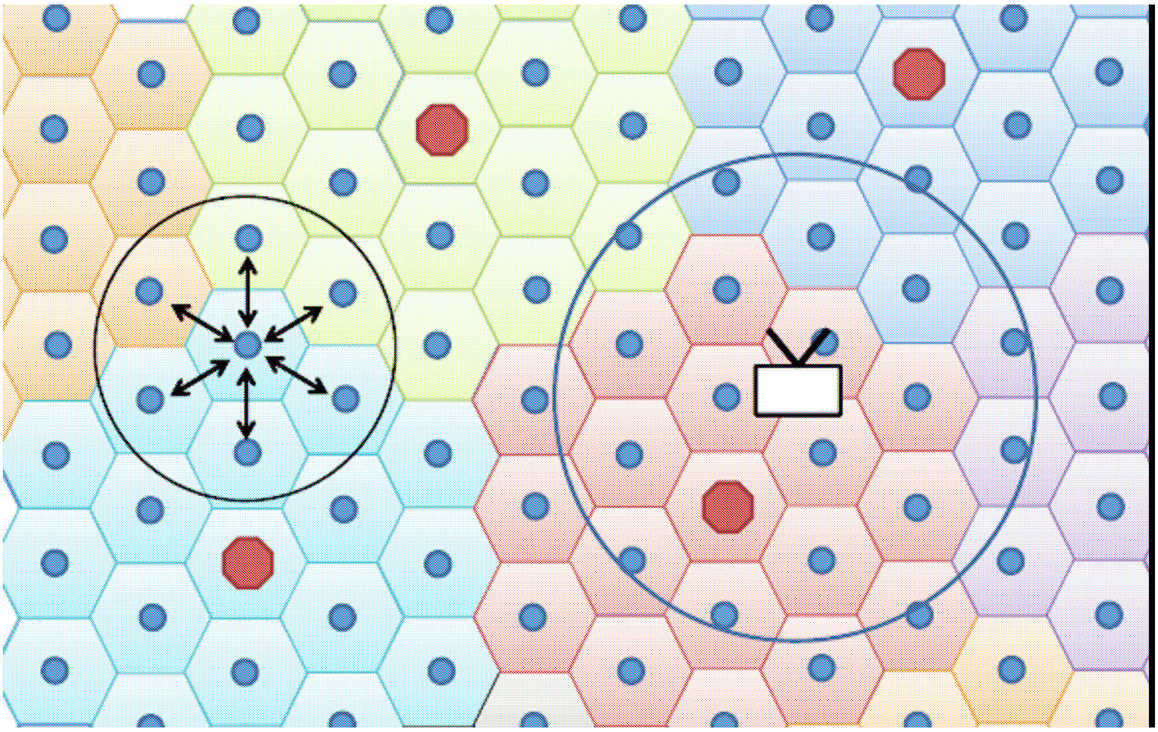

Figure 7: Network entities in the clustered architecture

Secondary Units Behavior

The secondary units contact the fusion centre (or the CHs) for frequency requests. The information provided with the request varies with the secondary network communications characteristics. For instance, assuming the secondary users have an omnidirectional antenna the requests should include secondary unit location (if available), and the transmit power (or the distance) which provides the information about the secondary user radio footprint. In case of directional antennas, additional information as the position of the secondary receiver (if available) and/or the angle of transmission should be also included.

Following the request, the secondary unit waits for the fusion centre (or cluster head) response with the assigned frequency. These frequency allocation messages are periodically received with updated channel assignment (or they can be elected by the secondary user itself) until the secondary disconnects himself. This functionality requires the definition of an interface between the cognitive radio network and the sensor network. As explained in Section 2, the protocols defining this interface will be developed in D4.2 of the SENDORA project. What is important to emphasize is that the secondary units communicate the location of the transmitter and its transmit power, or an equivalent information through this interface.

We point out that the secondary unit may not coincide with the secondary transmitter that needs to use the spectrum, for example, the cognitive network could be made of wireless users connected to a base station, and the base station plays the role of the secondary unit communicating with the WSN FC or CH, but providing the data of the mobile user that needs the band. Since the design of the cognitive network is outside the scope of the project, what matters here is that we assume that there is a secondary unit which is able to reach a cluster head or a fusion centre.

Sensors Behavior

Each node of the WSN senses the spectrum locally. A set of frequencies is sensed, local estimates are generated for all frequencies, according to the specific sensing algorithm: this can be as simple of a 0/1 decision or some more elaborate as a probability distribution. This vector of local estimates/decisions is available for distributed sensing. The set of frequencies as well as the width of the bands is a design parameter that has to be selected. If we follow SENDORA D2.1 specifications, we can choose to sense narrow bands of 200kHz.

Collaborative Spectrum Sensing

In many scenarios, as in the case described in Section 3.1, the spectrum sensing algorithm requires the exchange of information among nodes. Sensor cooperation can be performed at each sensor, during sensing information fusion, or after the sensing information fusion, at the FC or at a CH.

In the first case sensor nodes exchange information with their nearby nodes based on the *cooperation radius* (Rc). Rc is the number of sensor tiers that the node will exchange sensing information with in order to make a more reliable spectrum decision. If Rc is 1, the node will only exchange information with the first tier (one hop neighbors) as shown in Figure 3. If Rc is 2, the node will exchange sensing information with the nodes in the first and second tiers, that is with one hop and two hop neighbors. The collected information can be local estimate or local binary decision. After collecting this information, each sensor generates a global estimate for all sensed frequencies, based on some cooperation rule, which again can have binary outcome, or something more sophisticated, By the end of the process the vector of global estimates is ready to be transmitted to the fusion centre or cluster head.

Cooperative sensing can be performed during the aggregation process. In this case an aggregation tree is built to the FC or the CH. Sensors on the aggregation tree receive partial global decisions from the children nodes, combine it with their own local estimate and forward to the parent node. The global decision is finalized at the root of the aggregation three, the FC or the CH.

It is also possible to omit this step and construct the map directly at the fusion centre or the cluster head. The sensors send their local estimate to fusion centre (or CH) which builds the frequency map based on the gathered data and the nodes position according the collaborative sensing algorithm.

Sensor Estimate/Decision Dissemination

Sensor estimates/decisions need to be propagated to the fusion centre (or CH). If the spectrum decisions are carried out locally by the sensors the information propagated to the fusion centre (or CH) is the decision itself. Otherwise, the sensor sends the local estimates to the fusion centre which then carries out the decision step itself.

4.3 PROTOCOL STACK AND CONTROL FUNCTIONS

In this section we describe the protocol stack for the Sendora WSN. We consider the networking functions required for the fixed regular sensor network and for the ad-hoc case when sensors (embedded in the secondary units) are randomly placed and their location and density may change infrequently. We start with a brief summary of the typical protocol layers functionality depicted below.

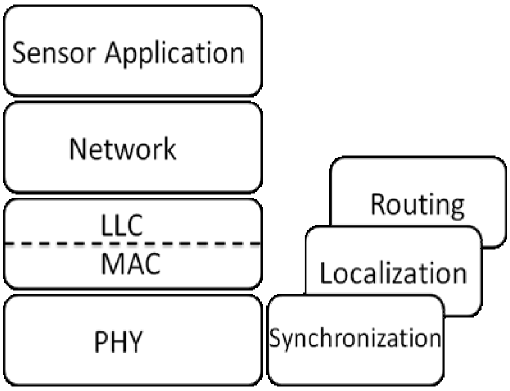

Figure 8: WSN protocol stack and control functions

Physical Layer (PHY)

An indicative set of functions that manipulate the sensed information are shown on Figure 9.

The information source outputs bits in a continuous stream or in packets. After source coding, encryption in the higher layers follow physical layer functions as channel coding and the mapping of bits into symbols belonging to a constellation. Each symbol of the constellation corresponds to a transmit waveform, or pulse. Then the pulse is modulated at RF and enters the transmission chain, power amplifiers, filters, and the antenna. At the receiver side, the inverse operations are performed.

For robust transmission the Physical layer has to be designed in close relation with the MAC layer in the sense that the wireless medium is shared among different users, in our case sensor nodes and other WSN elements, and with the Data Link Layer, where issues related to the recovery of packet errors are handled.

The modulation technique selected in the physical layer is strictly dependent on the available system bandwidth. In particular, for a given channel coherence bandwidth we will assume that if the system bandwidth is greater than the coherence bandwidth, the WSN will use a multicarrier modulation (e.g. OFDM). For a narrowband assumption (which is the main assumption in the project), instead, we will resort to QAM or BPSK modulation. At the level of the Sendora Wireless Sensor Network simulation environment, the activity on physical layer issues will have the scope to develop suitable models of performance in the packet reception. Considering analytical modeling we resort to the assumption of the 10kbit/s control channel as defined in D2.1.

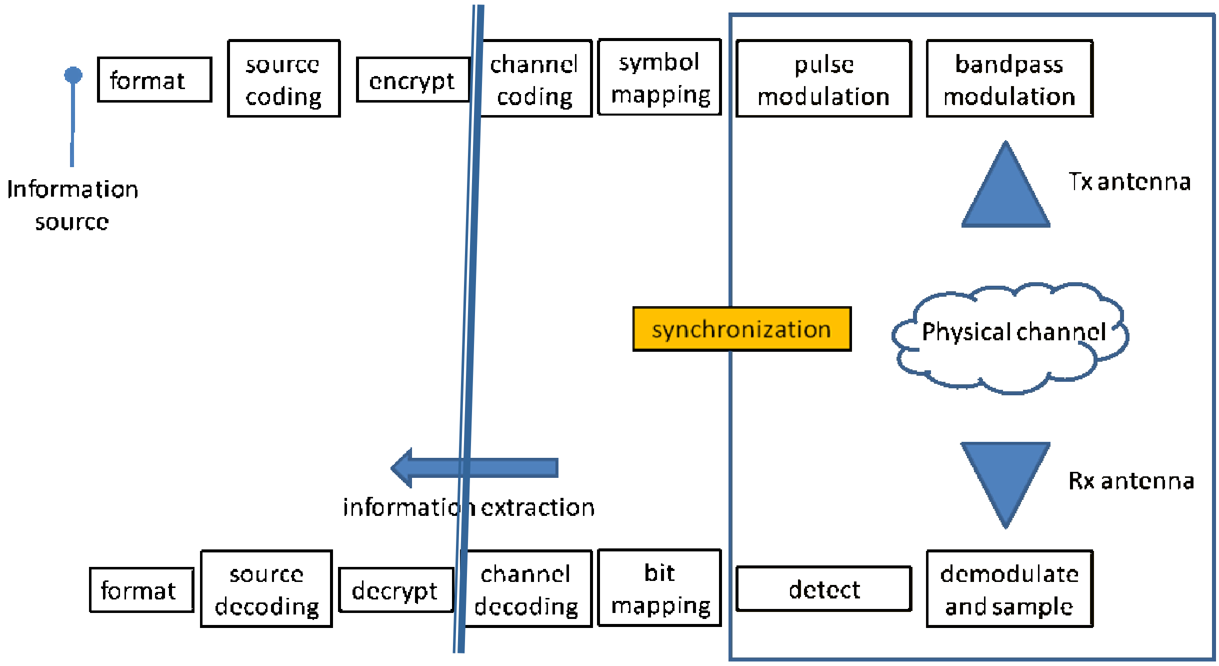

Figure 9: Functionalities of the lower layers of a wireless communication system.

Data Link Layer

In a sensor network, the two major services which the link layer provides to higher layers are: the creation of a network infrastructure by establishing communications links for hop by hop communications and, the mechanism for efficiently sharing the communications resources. Accordingly, the link layer is divided into the Logical Link Control (LLC) and the Medium Access Control (MAC) sublayers.

LLC sublayer

Error control – if any - is carried out by the LLC sublayer (and/or the PHY layer). The most used techniques are forward error correction (FEC) and automatic repeat request (ARQ). In FEC, redundant bits are added to information bits to detect and correct channel-induced errors. In ARQ, on the other hand, error control is achieved through retransmission of erroneous data packets. The main distinction between FEC and ARQ is in the trade-off between bandwidth overhead and packet recovery time. While FEC can help in quickly recovering from packet losses, the bandwidth overhead can be high especially over virtual links experiencing bursty losses. On the other hand, an ARQ based solution will have a high packet recovery time. In general, FEC guarantees better delay performance (no retransmission) at the cost of less available bandwidth (due to the use of redundant code). The two techniques can also be combined. Hybrid-ARQ is an ARQ system that is implemented together with FEC, providing improved link performance over traditional ARQ at the cost of increased implementation complexity. The simplest version of H-ARQ is a simple combination of FEC and ARQ, where blocks of data, along with a CRC code, are encoded using an FEC coder before transmission; retransmission is requested if the decoder is unable to correctly decode the received block. When a retransmitted coded block is received, it is combined with the previously detected coded block and fed to the input of the FEC decoder. Combining the two received versions of the code block improves the chances of correct decoding. This type of H-ARQ is often called type I chase combining. To further improve the reliability of retransmission, type II H-ARQ is also used. Unlike in type I H-ARQ, each (re)transmission is coded differently to gain improved performance. Typically, the code rate is effectively decreased every retransmission.

Choice of the error control scheme depends on the application requirements. In Sendora, given the tight maximum response time (see Section 2.2), FEC is to be preferred to ARQ to ensure timely delivery of sensing and control information among nodes. ARQ is used for single messages like the SN bandwidth request.

MAC sublayer

Turning our attention to the MAC sub-layer, there are different approaches to channel access, namely contention based and collision free protocols with explicit organization in time/frequency/code domains. CSMA based protocols as 802.11 are notable examples of the former approach. The second approach attempts to determine the network radio connectivity first, i.e. discover the radio neighbors of each node, and then assign collision-free channels to links. The task of assignment of channels, i.e. TDMA slots, frequency bands or spread spectrum codes, to links between radio neighbors such that they do not collide is a hard problem. These methods of channel access require nodes in the network to be synchronized with each other at some level (usually at the slot boundary epochs for TDMA systems). In these schemes, usually a period is set aside for neighbor discovery and TDMA schedule construction. If a centralized channel assignment algorithm is to be used, the entire connectivity information along with any bandwidth requirements for specific links are passed to a single node in the network for the calculation of a schedule. Under distributed assignment nodes exchange connectivity data in some local neighborhood and converge to a common scheduling. To ease the assignment problem a hierarchical structure can be formed in the network to localize groups of nodes and create per group schedules. An extensive summary of MAC protocols applicable for sensor networks is given in [28].

Considering the Sendora WSN, it is clear that most of the sensor network traffic is periodic and is exchanged among neighboring nodes, with additional convergecast communication to the FC of the frequency decision or CH to CH message exchange.

Therefore we propose spatial reuse TDMA based MAC protocol for controlling the access to the single communication channel, as it provides collision-free transmission which efficiently supports periodic traffic stream. In addition collision based periods has to be included for non-periodic message exchanges. For the fixed, regular WSN scenario the TDMA schedule is formed at the sensor network setup. In the ad-hoc case with irregular and slowly changing topology we need to resort to an infrastructure building protocol that enables nodes to discover their neighbors and establish transmission/reception schedule. Since periodic traffic is expected in this case as well, TDMA is still preferable. The schedule can be build together with the sensing tree construction rooted at the FC, the CH or at the sensor closest to the secondary unit in the fully distributed case.

Network Layer – Routing

Routing is significantly different from routing in traditional networks due to the inherent characteristics of sensor networks which range from lack of global addressing, data-centric nature of applications and the often energy constrained nature of nodes. Many different approaches to routing in sensor networks have been proposed in the literature [29].

In flat routing all the nodes take the same responsibility in maintaining routing information for relaying packets. These include the well-known directed diffusion protocol [32]. The FC requests data by broadcasting interests. The interest describes a task required to be done by the network. It diffuses through the network hop-by-hop as it is broadcasted by each node to its neighbors. Each sensor that receives the interest sets up a gradient toward the sensor nodes from which it received the interest. Gradients are then used to forward data from the sensors to the base station.

In hierarchical or cluster-based routing, nodes are arranged in clusters in order to achieve routing scalability. Cluster heads may have assigned special tasks including data aggregation and fusion. Hierarchical routing works as a two-layer routing where one layer is used to select and transmit to cluster heads and the other is to route multi-hop messages between cluster heads.

In location based or geographical routing, sensor node positions are exploited to route data in the network. Nodes are supposed to know or to estimate their positions. Routing is carried out by forwarding packets to the node (or nodes) towards the destination.

To evaluate the routing requirements in the spectrum sensing WSN, let us summarize the communications patterns among nodes. From scenario description, we recognize the following types of traffic:

- Periodic traffic exchange among neighboring cooperating sensing nodes for local cooperative sensing (up to the cooperation radius R_c);
- Control message from the fusion centre (or cluster head) to the sensor nodes for activating/deactivating sensing;
- Periodic diffusion of data from the sensor node to the fusion centre (or cluster head);
- Frequency/Bandwidth request from the second user to the fusion centre (or cluster head).

Since efficient routing depends on the level of centralization in the WSN, we discuss the specific routing solutions in the next section together with the detailed description of the centralized and the cluster based protocol stack.

Localization

In our application, there are two types of localization which are crucial to network operation: sensing node location and secondary user location. Information on the sensor position is needed to associate their frequency availability information to the respective position. The sensor position is also needed in cooperative sensing since the relative node position is required by most algorithms. The secondary users location is also needed by the fusion centre to properly determine the area potentially interested by the SU transmission. Considering the target scenario of the project, the sensor and secondary user positions are static or quasy-static, which makes localization less challenging.

The goal of localization is to determine the physical coordinates of a node. These coordinates can be global, meaning they are aligned with some externally meaningful system like GPS, or relative, meaning that they are an arbitrary “rigid transformation” (rotation, reflection, translation) away from the global coordinate system.

In the fixed, regular WSN, the position of the sensor nodes can be hard coded at the network deployment. Another immediate solution to the localization problem is the Global Positioning System (GPS). However, we cannot assume in general that all sensor nodes and secondary units are equipped with a GPS antenna. In this case, nodes need other means to establish their position. An overview of state of the art localization techniques and related open issues is presented in [30].The definition of new localization techniques or the effect of localization errors on the system performance is not in the main focus of the project. For the performance evaluation we will simply assume that an appropriate localization protocol is in place. Below we discuss one possible solution.

For the localization of the SENDORA secondary users (and the spectrum sensors of the secondary users in the ad-hoc case) we propose a simple beacon based multilateration approach [31]. In this case some of the sensor nodes, e.g., the cluster heads, send periodic beacon packets with well known power. Ideally, the energy of a radio signal diminishes with the square of the distance from the signal source. As a result, a node listening to a radio transmission should be able to use the strength of the received signal to calculate its position using the algorithm described below. At a minimum, three non-collinear beacon nodes are required to define a global coordinate system in two dimensions. More signal increases the localization precision. In practice, however, ranging measurements contain noise on the order of several meters. This noise occurs because radio propagation tends to be highly non-uniform in real environments. Physical obstacles reflect and absorb radio waves. As a result, distance predictions using signal strength are affected by error which could negatively impact SU operation.

Multilateration localization

We now provide a simple algorithm for the multilateration problem using beacon signals [31]. Multilateration is a simple technique which solves the following problem, as shown on Figure 10: given *m* nodes with known Cartesian position b_i, i =1,…,m and possibly noisy range measurements r_i, from the known nodes to an unknown node s, find the most likely position of s.

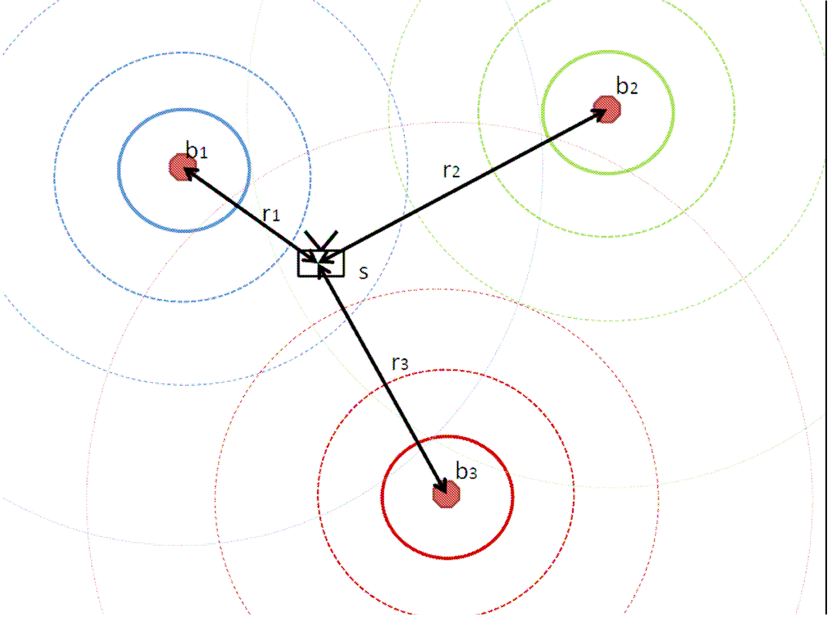

Figure 10: Localization of a SU using CHs as beacons.

Multilateration is typically done by minimizing the squared error between the observed ranges r_i and the predicted distance $\|s-b_i\|$:

$$s = \underset{s}{\operatorname{argmin}} E(s)$$

$$E(s) = \sum_{i=1}^{m} (\|s - b_i\| - r_i)^2$$

This minimization can be solved iteratively using the least-square Newton-Raphson algorithm as follows. First approximate the error function $e(s,b_i) = \|s - b_i\| - r_i$ with the first order Taylor series expansion about s_0 :

$$\begin{aligned} e(s,b_i) &\approx e(s_0,b_i) + \nabla e(s_0,b_i)(s - s_0) \\ &= \nabla e(s_0,b_i)s - (-e(s_0,b_i) + \nabla e(s_0,b_i)s_0) \\ \nabla e(s_0,b_i) &= \frac{s - b_i}{\|s - b_i\|} \end{aligned}$$

Plugging this approximation in the equation above yields:

$$s \approx \underset{s\sum_{i=1}^{m}\left(\nabla e(s_0,b_i)s-\left(-e(s_0,b_i)+\nabla e(s_0,b_i)s_0\right)\right)^2}{\mathbf{argmin}}$$

Which can be rewritten as follows:

$$\begin{aligned} s &\approx \underset{s}{\mathbf{argmin}}\|As - b\|^2 \\ A &= \begin{bmatrix} \nabla e(s_0,b_1) \\ \nabla e(s_0,b_2) \\ \vdots \\ \nabla e(s_0,b_m) \end{bmatrix} \\ b &= \begin{bmatrix} -\mathbf{e}(\mathbf{s_0},\mathbf{b_1}) + \nabla e(s_0,b_1)s_0 \\ -\mathbf{e}(\mathbf{s_0},\mathbf{b_2}) + \nabla e(s_0,b_2)s_0 \\ \vdots \\ -\mathbf{e}(\mathbf{s_0},\mathbf{b_m}) + \nabla e(s_0,b_m)s_0 \end{bmatrix} \end{aligned}$$

The quadratic problem above can be solved via standard least square solvers. The resulting position s is a good estimate of the unknown position r_i. The summary of the overall algorithm is as follows:

Step 1 Choose s_0 as a starting point. A good choice is provided by the centroid of the know position $b_i, \bar{b} = \frac{1}{m}\sum_{i=1}^{m} b_i$.
Step 2 Compute A and b.
Step 3 Find $s_0' = \arg\min_s ||As - b||^2$ using a least square solver.
Step 4 If $|E(s_0) - E(s_0')| < \epsilon$ then s_0' is the solution. Otherwise, $s_0 = s_0'$ and return to step 2.

Synchronization

Time synchronization in networks and computer systems in general, aims at providing a common time scale. Since all hardware clocks are imperfect local clocks, they eventually drift away from each other over time. However in many applications and network protocols a common view of time is required for correct operations. In wireless sensor networks, sensed data need to be associated to a correct timestamp; otherwise operation as data fusion or in general any type of correlation of data from different nodes cannot be carried out. In addition, all time division multiple access schemes– as TDMA – require clock synchronization. A possible solution lies again in the use of GPS (which provides accuracy range from 500 nanoseconds to 1 millisecond). Without GPS, synchronization can be achieved in a sensor network using distributed algorithms which differ in terms of performance, complexity and number of required control messages [36].

Synchronization can be achieved in different ways[1]. For its simplicity and scalability we use the Timing-Sync Protocol for Sensor Network [36]. The protocol works in two phases: a *level discovery phase* and *synchronization phase*. The aim of the first phase is to create a hierarchical topology in the network, where each node is assigned a level. Only one node is assigned level 0, called the *root node*. In the second phase, a node of level *i* synchronizes to a node of level *i*-1. At the end of the synchronization phase, all nodes are synchronized to the root node and the network-wide synchronization is achieved. In the following we describe the solution within SENDORA (which is an adaptation from [36]) referring to the clustered solution for ease of presentation. Simple adjustments can be made to for the centralized solution.

Level Discovery Phase This phase is run once at the network deployment. First a node should be determined as the root node. In Sendora WSN, this can be any CH which takes the role of primary CH to which the other CHs and nodes synchronize to (If the CH has a GPS receiver, the algorithm will synchronize all nodes to the GPS reference clock). The primary CH is assigned level 0, and initiates the level discovery phase by broadcasting a *level discovery* packet. This packet contains the identity and level of the sender node. Upon receiving this packet, the neighboring CH of the primary CH assign themselves level 1. Then each level 1 CH broadcasts a *level discovery* packet with its level and identity in the packet. Once a CH is assigned a level, it discards further incoming *level discovery* packets. This broadcast chain goes on through the network, and the phase is completed when all CH are assigned a level.

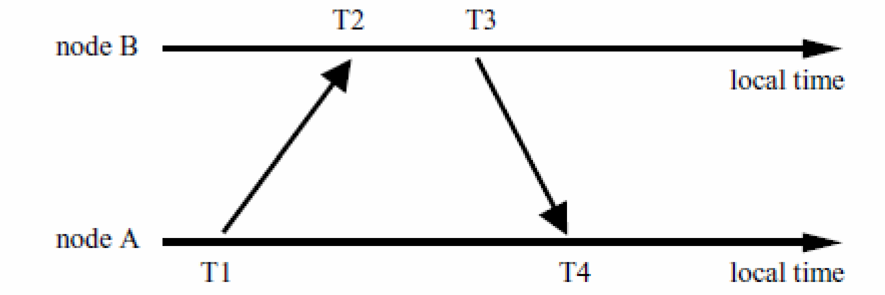

Figure 11: Two way message exchange between two pair of nodes (at level i and i-1, respectively)

Synchronization Phase The basic building block of the synchronization phase is the two-way message exchange between a pair of nodes. Consider a two-way message exchange between nodes *A* and *B* as shown in Figure 11. Node *A* initiates the synchronization by sending a *synchronization pulse* packet at $T1$ (according to its local clock). This packet includes *A*'s level number, and the value $T1$. *B* receives this packet (according to its local clock) at $T2 = T1+\Delta+ d$, where Δ is the relative clock drift between the nodes, and d is the propagation delay of the pulse. *B* responds at time $T3$ with an acknowledgement packet, which includes the level number of *B* and the values $T1$, $T2$, and $T3$. Then, node *A* can calculate the clock drift and propagation delay as below,

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[1] Both OpenAirInterface topologies require Network Synchronization (NS) at least between adjacent clusters. This must be on the order of a few microseconds. Three mechanisms are supported to ensure NS. Firstly, a secondary synchronization source (e.g. GPS) can be used as a common time reference by all nodes. Secondly, one CH (Primary CH) in the network use a special synchronization signal which has longer range than the range of communication, in order to cover the region with a common time reference. This is suitable for small networks. Finally the method of distributed relaying of synchronization is possible. This is a method by which all nodes propagate a time reference. Nodes switch between reception (for timing acquisition and tracking) and transmission of the reference. This guarantees coverage of network synchronization over long distances in the absence of a secondary synchronization source.

$$\Delta = \frac{(T2 - T1) - (T4 - T3)}{2} \text{ and } d = \frac{(T2 - T1) + (T4 - T3)}{2}$$

and synchronize itself to B. The synchronization phase is initiated by the root node's *time sync* packet. On receiving this packet, level 1 CHs – and all primary CH cluster nodes - initiate a two-way message exchange with the primary CH. Once they get back a reply from the root node, they adjust their clocks to the root node. Level 2 CH – along with level 1 CH cluster nodes – overhearing some level 1 CH's communication with the primary CH, initiate a two-way message exchange with a level 1 CH. This procedure eventually gets all nodes synchronized to the root node.

This synchronization procedure should be run periodically to ensure proper level of synchronization among nodes. We leave the computation of the proper periodicity to future work.

4.4 PROTOCOL STACK FOR THE REGULAR SENSOR NETWORK SCENARIO

In the following, we describe the functionalities of each component of the WSN protocol stack considering the centralized and the cluster based architecture for the fixed, dedicated spectrum sensing WSN. We also define which components will be developed in the project and which ones we will assume to be existing, e.g. synchronization protocols, node identification, and so on. Finally, we describe in detail the medium access control for local cooperative sensing support, which is applicable to both centralized and cluster based architectures.

4.4.1 Centralized architecture specific protocol design

In some operative scenarios it is realistic to think that the distributed sensing operation for the identification of spectrum holes is carried out at a single node that is called fusion centre. For example when the spectrum occupancy dynamics of primary users are relatively slow, e.g. primary users are TV stations, or the area of cognitive operation is small and the number of secondary users is not that high. In such cases, the burden of communication and processing may be light enough to be handled by a single entity.

In the following we describe a protocol stack framework that identifies the necessary components of the WSN protocols stack, and provides a platform that to discuss in detail the specific protocol implementations, both here and in the forthcoming deliverables.

The key network entities involved in the cognitive cycle are:

CRN-E: Cognitive Radio Network Entity: this identifies the node of the secondary network that interfaces the secondary wireless sensor network, forwarding request for channel availability for itself or, possibly, for other nodes of the secondary network. For example, the secondary network can have base-stations or sink points that collect requests of channels from secondary users and forward them to the WSN, or it could be each SU that directly interfaces with the WSN.

FC: Fusion Centre: it is the sink node responsible of handling on one side the spectrum sensing outcomes of the sensors, and the requests for channel availability on the other side.

Sensors: the nodes of the sensor network sense the spectrum and can take decision on spectrum bands occupancy at the local level. To do this they can interact with neighbors to obtain more reliable estimations/decisions. The local decisions are then forwarded to the FC for further elaboration either proactively or upon specific trigger from the FC. Figure 12 depicts the information flows among these entities.

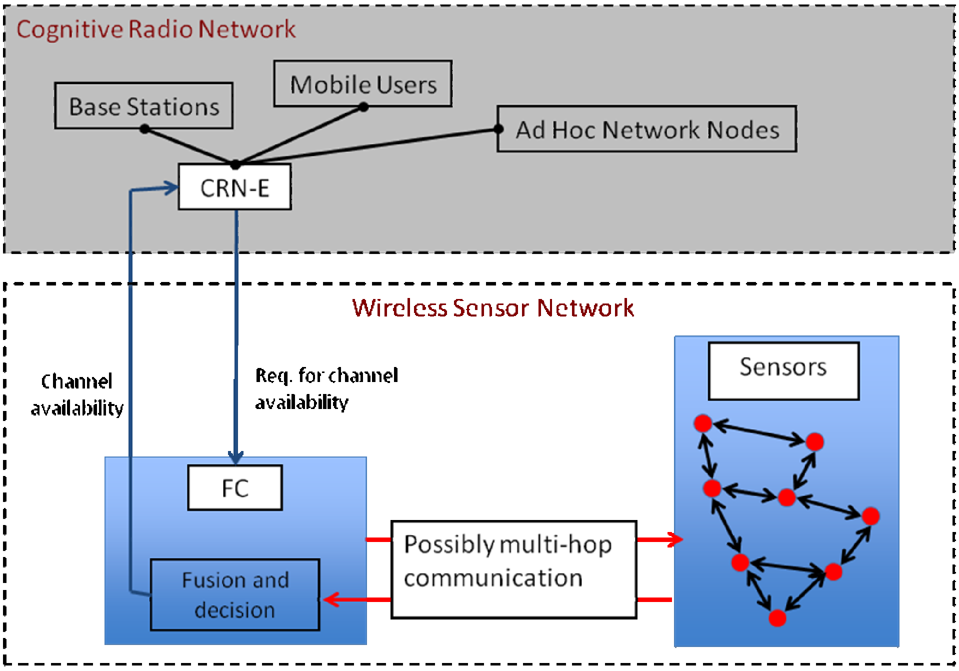

Figure 12: Centralized architecture. Information flows for the WSN and at the cognitive network-WSN interface.

We can readily identify three information flows, or traffic types, each of which requires its own protocol stack. Furthermore, it is clear that a strong coordination among these three information flows is required.

The following table specifies the protocols required by each one of the above described flows, or traffic types: the color of the text in the left column reflect the color of the arrows in Figure 12 corresponding to the same flow. In the right column, the lines in black represent protocols that will be implement and tested, whereas the grey lines represent elements that will be assumed as existing and working.

IS (Inter-sensor) Protocols	Syncronization Multiple Access
S2CH (Sensors to ClusterHeads) Protocols	Syncronization Sensor association (ID-based) to a cluster Localization MAC Routing
CRN-WSN Protocols	

Table 2: Protocols specific for given traffic types in the centralized configuration

<u>Inter-Sensor</u> (IS): Communications and Protocols:

At this layer, inter-sensor communication takes place with the scope of refining the local decision/estimate on spectrum occupancy of each cell. These protocols basically implement a cooperative sensing algorithm. The only protocol that will be implemented is the MAC protocol. This MAC protocol is the same for the centralized and cluster based architectures and is described in Section 4.4.3.

Sensors-to-Fusion Centre (S2CH): Communications and protocols:

Local estimates/decisions (as an output of the cooperative sensing algorithm, or as purely local decisions) are forwarded to the fusion centre for fusion and communication of the available channels to the CRN-E.

One aspect that deserves attention is the *Routing of control message* from the fusion center to the sensor nodes for activating/deactivating sensing: in the reactive scenario, the fusion center needs to activate sensor measurements and collect the sensing data from the portion of the network interested by the secondary user transmissions. To this end, routing should support efficient mechanism to send requests/collect data from specific area of the network. In this case flooding appears an inefficient solution since the requests would be broadcasted to the entire networks.

A simple routing solution is represented by geographic routing with data scoping. In geographic routing, sensor nodes are addressed by means of their locations. Geographic routing protocol use greedy algorithms to forward packets to the destination: when one or more closer neighbors to a destination exist the algorithm picks a next-hope node among all neighbors that are close to destination.

Data scoping under geographic routing, as in GEAR [37], provides an efficient way to disseminate a geographically scoped query/interest by using the knowledge of the destination location and routing a query/interest directly to the destination region rather than just flooding it everywhere. In this scheme a query is geographically routed to the target region. Once inside the region, a simple limited flooding with duplicate suppression (or a more sophisticate scheme) can be used to flood the packet in the region. As the query/interest is distributed, traversed nodes establish gradients, which will be used to propagate data back.

Above we assumed that the set of sensors providing the sensing information is known. In Section 4.5 we address the problem of optimizing routing together with the selection of sensors that should provide sensing information about a particular area or active primary user.

CRN-WSN: Communications and protocols:

The fusion centre interacts with the CRN-E to handle requests for transmission from secondary users and to communicate them the available channels. This communication requires simple point to point routing protocols. This communication is addressed in WP4.

4.4.2 Clustered architecture specific protocol design

Figure 13 gives a sketch of the nodes functionalities to be implemented by the protocol stack. The Cognitive Radio Network Entity (CRNet-E) is the secondary network unit that interfaces directly with the sensor network, and in particular with the cluster head, making its request for frequency availability.

For the feasibility of the request, it is necessary that the SU knows what CH to contact, i.e. it knows in which cluster of the WSN it is located. To allow the connection to a CH, the cluster heads periodically send messages with their own I. We assume, that there is no point in the service area that is not reached by the beacons coming from at least three different cluster heads.

When a cognitive user needs spectrum availability information, it detects the CH ID messages and connects to the CH with the strongest signal. In typical scenarios, this is the CH of the cluster the SU is located in.

Notice that, in principle, the detection of at least 3 cluster heads makes it possible to perform a coarse localization of the SU cell within the cluster. The localization algorithm can be performed either by the SU, or by the CH upon reception of the SU request.

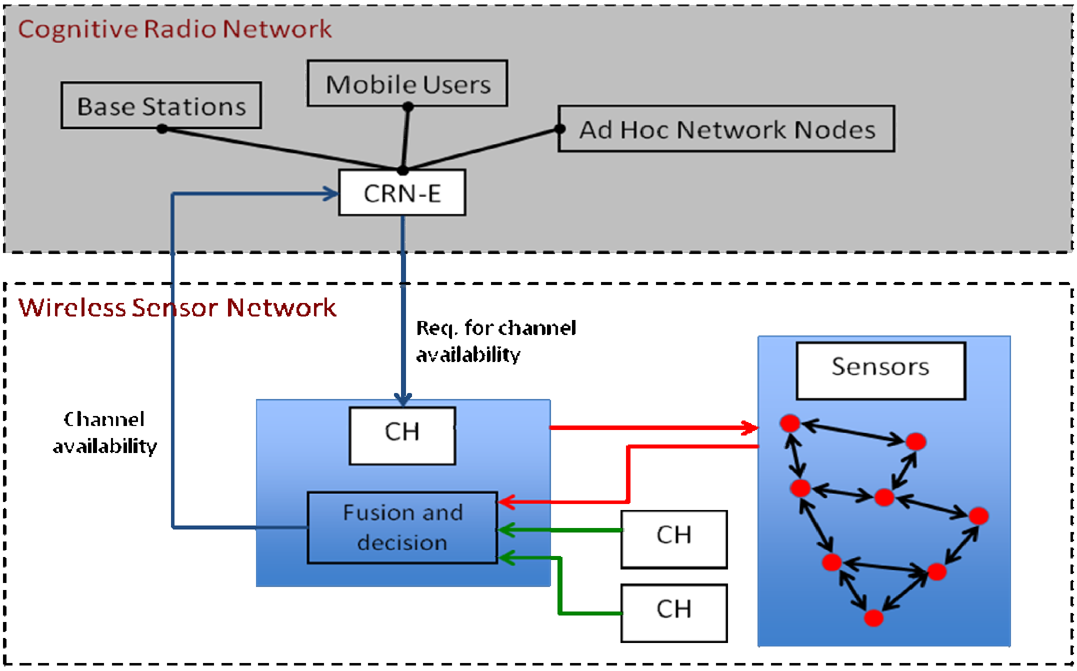

Figure 13: Clustered architecture: Information flows within the WSN and at the cognitive network-WSN interface.

When a CR user wants to transmit, the CRN-E (could be the SUtx itself) sends a message to the CH of its cluster, communicating the position (cell) of the SUtx. Alternatively, it communicates the information of the signal strength received by the backbone nodes, with the respective ID, in which case the localization algorithm is performed at the CH. Furthermore, the SU communicates the transmission range it wants to reach. The CH knows now the position of the SU, and thanks to the transmission range information it calculates the cells covered by the radio footprint of the SU.

If the reactive or hybrid approach is employed, the CH makes request for spectrum occupation in the involved cells to the other cluster heads. In the completely proactive case, the CH could already have this information. Upon collecting this information, it is able to provide the CRN-E with the available channels.

The table below describes the protocol stack of the clustered wireless sensor network architecture. In the right column, the lines in grey mean that we will assume the corresponding protocol as existing, whereas the other ones will be implemented. In the left column, the colors of the text reflects the color of the arrows in Figure 13.

IS (Inter-sensor) Protocols	Syncronization

	Multiple Access
S2CH (Sensors to Cluster Heads) Protocols	Syncronization Sensor association (ID-based) to a cluster Localization MAC Routing
ICH (Inter-ClusterHead) Protocols	Syncronization MAC Routing
CRN-WSN Protocols	

Table 3: Protocols specific for given traffic types in the clustered architecture

Inter-Sensor (IS): Communications and Protocols:

At this layer, inter-sensor communication takes place with the scope of refining the local decision/estimate on spectrum occupancy of each cell. These protocols basically implement a cooperative sensing algorithm. The only protocol that will be implemented is the MAC protocol described in Section 4.4.3.

Sensors-to-Cluster Heads (S2CH): Communications and protocols:

Local estimates/decisions (as an output of the cooperative sensing algorithm, or as purely local decisions) are forwarded to the cluster heads for fusion and communication of the available channels to the CRN-E. One aspect that deserves attention is the routing of control message from the cluster head to the cluster sensor nodes for activating/deactivating sensing:

In the reactive scenario, the CH needs to activate sensor measurements and collect the sensing data from the portion of the network interested by the secondary user transmissions. To this end, routing should support efficient mechanism to send requests/collect data within its cluster. A simple solution consists in broadcasting the request (interest) to the cluster and then collect the data sent by the sensors. This is a well known situation in the literature which can be efficiently handled via direct diffusion in the area.

Direct diffusion is a data centric routing scheme for wireless sensor networks. The CH activates the sensors and requests data by broadcasting interests. Interest describes a task required to be done by the network. Interest diffuses through the cluster hop-by-hop, and is broadcasted by each node to its neighbors. As the interest is propagated throughout the cluster, gradients are set up to draw data satisfying the query towards the requesting CH. Each sensor that receives the interest sets a gradient up toward the sensor nodes from which it receives the interest. This process continues until gradients are set up from the sources back to the CH. More generally, a gradient specifies an attribute value and a direction. The strength of the gradient may be different towards different neighbors. This can be augmented via a Gradient Based Routing (GBR). GBR is a variation of the direct diffusion routing. The key idea in GBR is to memorize the number of hops when the interest is diffused. As such, each node can calculate a parameter called the height of the node, which is the minimum number of hops to reach the CH. The difference between a node's height and that of its neighbor is considered the gradient on that link. Response data from the sensors are then just forwarded on the link with the largest gradient or randomly among those with largest gradient in case of ties.

Inter-Cluster Head (ICH): Communications and Protocols:

A CH that is handling a request of transmission from a CRN-E in its cluster has to communicate with neighbour CHs to receive information on the spectrum occupancy of cells located in their cluster and that are part of the radio footprint of the SUtx that has given rise to the request (through the CRN-E).

CRN-WSN: Communications and protocols:

CHs interact with the CRN-E to handle requests for transmission from secondary users and to communicate them the available channels.

It is important to say that the communication of the set of available channels does not solve the Medium Access Control Problem of the secondary network. To address this problem one should specify the architecture of the secondary network and its MAC protocol. This issue falls within the goals of Deliverable D4.2 on cognitive actuation. Therefore,WP6 does not specify how the available channels are accessed by the cognitive users.

4.4.3 MAC protocol for distributed sensing

In the following, without lack of generality, we assume sensors are arranged as a triangular grid. The analysis that follows can be generalized to any regular topology [33]. Nodes known their location and are assigned a unique ID (Since the topology is assumed to be fixed in this scenario, this information can be safely assumed to be preconfigured in the node). Since we are considering a network of homogeneous nodes, we will assume that all nodes are characterized by a given transmission range R_t and interference range R_i.

Given the traffic pattern, a simple and efficient solution is the spatial reuse TDMA (STDMA). TDMA is a schedule based MAC protocol that controls the access to a single channel. TDMA provides collision-free transmission since a set of time slots are prearranged. Spatial reuse TDMA is an access scheme for multi-hop radio networks. The idea is to increase capacity by letting several radio terminals use the same time slot when possible. A time slot can be shared when the radio units are geographically separated such that small interference is obtained. A TDMA scheme is defined by its frame length (number of slots) and schedule, i.e., which slot is assigned to which sensor. In a STDMA, spatial reuse implies that a slot is assigned to multiple sensors if the sensors cannot cause interference at a potential receiver to other transmissions.

Optimal, i.e., minimum length, slot assignment depends on the nodes communication pattern and is in general NP-complete. Given the complete symmetry of sensor behavior we resort to a simple sub-optimal algorithm, introduced in [35] to address a different problem (the channel assignment problem in cellular networks), which allows us to formalize the problem a Distance-k Chromatic Number Problem

Distance-k Chromatic Number Problem: Given a graph G=(V,E) and an integer k, the distance-k chromatic number of the graph is the fewest number of colors needed to color the nodes of the graph so that no two nodes of the graph have the same color if the shortest path length (measured in number of intervening nodes) between the nodes is less than or equal to k. Such a coloring of the nodes of the graph is known as a proper coloring.

In [35] the authors provide a schedule which requires $k^2 + k + 2$ slots.

In our setting, if we regard color as slots, the problem becomes finding the minimum number of slots which can be assigned to nodes so that there are no pairs of nodes closer than *k* which have been assigned the same slot. It is easy to realize that in our case $k = R_t + R_i$, i.e., the minimum distance between two nodes that can transmit at the same time. Hence the minimum number of slots is $(R_t + R_i)^2 + (R_t + R_i) + 1$. The minimum number of slots thus grows with the square of $R_t + R_i$. The first few values are listed in the following Table 4.

$R_t + R_i$	Minimum number of slots
1	3
2	7
3	13
4	21

Table 4: Transmission ranges and time slots

Observe that since the number of slots is proportional to the frame length, and thus inversely proportional to the frame rate, the data rate available to each node decreases for increasing value of both the transmission and interference range.

The following figures illustrate the STDMA assignment for different values of R_t and R_i. In each figure, for a given R_t,R_i pair, and considering a particular slot, we show which nodes can transmit at the same time (the red nodes) and their transmission (green area) and interference (blue) area.

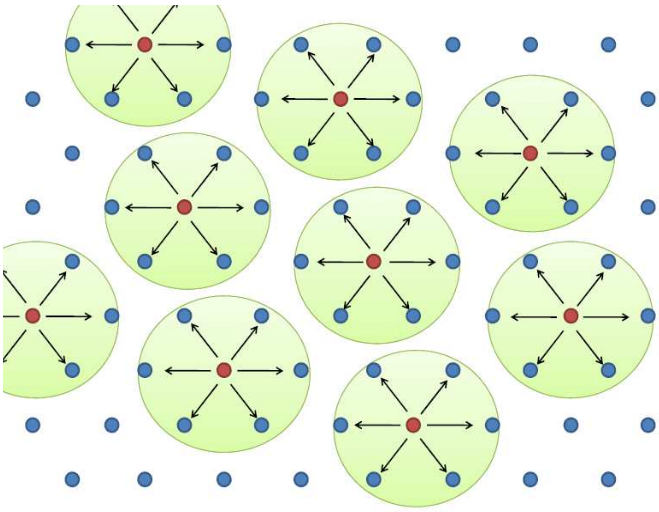

Figure 14: $R_t = R_i = 1$

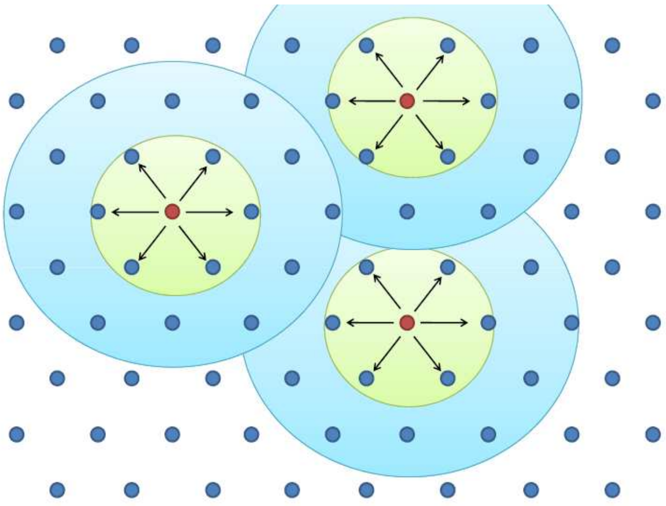

Figure 15: $R_t = 1, R_i = 2.$

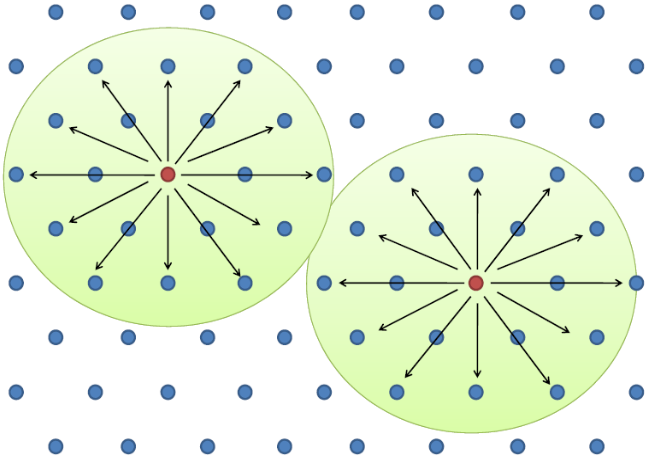

Figure 16: $R_t = R_i = 2$

These figures show as fewer and fewer nodes can transmit simultaneously with increasing R_t and R_i. With $R_t = R_i = 1$, nodes that are 3 hops apart (*k*=2, two intervening nodes) can transmit simultaneously. In this case the minimum number of slots is 7. Increasing the interference range to 2 requires nodes to be 4 hops apart for simultaneous transmission (the overlapping of the blue area on Figure 15, the interfering range, is not a problem since the potential receivers are only those within the transmission range). Increasing now the transmission range from 1 to 2, requires even more slots since the distance in hops between transmitting nodes increases to 5.

The analysis above considers nodes constantly spaced and studies the effect of increasing transmission/interference range. The same type of results apply if we consider constant transmission/interference range and increase node density (thus shortening the distance among nodes).

4.5 OPTIMIZED SENSOR SELECTION AND ROUTING

The scenario currently at hand takes into consideration a primary user network (PUN) and an existing WSN grid taking measurements in a time-slotted scheme. The sensing and actuation process considered is the same as the one described in Section 3.1. Locally, samples are acquired, aggregated, and processed within one time frame. Consequently, at the next time-frame the latter information becomes available for the rest of the neighbouring nodes and as well as at a secondary base-station (BS) or a FC. A SU would consult the grid or the BS or a FC for knowledge on spectrum availability.

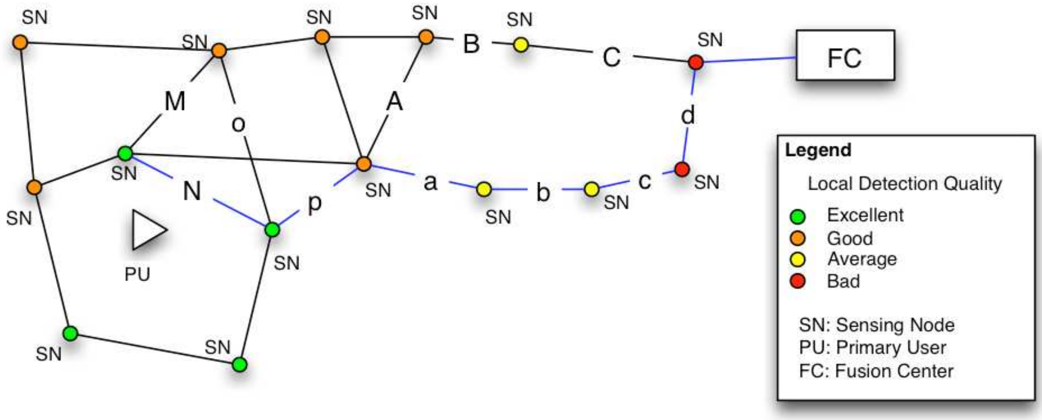

Figure 17: Sequential detection with joint routing trade-off: energy efficiency and detection reliability

The problem is illustrated further in Figure 17 by considering a randomly deployed network. Suppose that a sequential detection process is initiated and the first node has to choose between link *M* and link *N*. We would like to note that we do not concentrate on how the process is initiated as this is out of the scope of this section, however one suggestion is through SNR-gossiping algorithms where a consensus is reached on the node with the highest SNR, which would in turn initiate the detection process. According to power consumption, which under a first order approximation, is proportional to the distance raised to a certain exponent, link M seems to be the best choice. However, link N may provide a better choice in terms of detection as the next-hop neighbour is closer to the PU. Let us assume that link N is selected. The next node chooses link *p* over *o* as the former choice is more energy efficient, while the detection quality is negligibly affected. From thereon and with the same line of reasoning route *a*, *b*, *c*, *d* is chosen over route *A*, *B*, *C*.

As we can see from the example, the optimization problem at hand should consider a cost function that provides a trade-off between two axes, energy consumption and probability of detection (P_D). Thus, in the vicinity of the PU, P_D should be the principal factor in the cost function and vice versa as the route diverges away from the PU.

There are two main issues in the joint distributed-detection and routing problem. First, a pivotal decision should be made which is to determine the role of the local node in the global decision. The question is, do we need optimal local decision rules (or thresholds) or optimal weight factors for the sensors' aggregated samples? The other important issue in our problem is to combine sequentially local results while simultaneously routing them towards a specified data sink (BS or FC). The route should be chosen to be pareto-optimal in terms of global detection probability and energy consumption. The problem is defined in detail in Annex C.