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Abstract—This paper proposes and evaluates three business case scenarios for deployment of a sensor network aided cognitive radio system in a typical European city. The first and main business case is based on spectrum sharing, where several spectrum owners establish a joint venture and this joint venture gets the rights to use the “unused” spectrum resources of all those spectrum owners in a cognitive way. Then we study the business case of a spectrum broker, an entity that deploys, builds and operates a sensor network and sells either sensing information or information on spectrum opportunities to one or more cognitive radio operators. Finally we analyze the potential of a new entrant without existing infrastructure or frequency licenses, that uses a sensor network aided cognitive radio system to offer a nomadic mobile broadband service. It is found that the spectrum sharing business case is one of the best possible cases for the studied system because the joint venture operator has free access to frequency resources of the mother companies, detailed knowledge of the primary systems and good possibilities for sharing infrastructure with the owning operators. However, since the studied system is an innovative concept and some of the assumed parameters are therefore uncertain, it should be noted that the main value of the business case calculations is to identify critical aspects influencing the profitability so that future research and development work can focus on them. It is found that the most critical aspects are the fixed sensor density, the fixed sensor operational costs and the number of new cognitive base station sites required.

Keywords: cognitive radio, business case, sensor network, spectrum sharing, spectrum broker, new entrant

I. INTRODUCTION

Most research and development work on cognitive radio (CR) focuses on pure technical aspects of the technology. However, in order for an operator to be interested in deploying CR based networks the anticipated costs must be in proportion to what the users are realistically willing to pay for the service. Hence, techno-economical studies should be done in parallel with the technical research and development work to ensure that the solutions found are both technically and economically viable.

Since CR is an open and relatively new research field, there is a lot of uncertainty associated with many of the parameters needed in business case analyses. But even with uncertain input parameters the business case studies can be used for identifying critical parameters that must be considered in the technical studies. A good way to proceed towards a viable solution is to do the business case calculations and technical calculations iteratively, each time using the latest results of one to derive the input parameters to the other.

In this paper we study business cases for a sensor network aided CR scenario [1] that consist of three main networks; a primary network, a secondary CR network, and a sensor network which might be a separate network and also embedded in the cognitive network. Three business cases are studied, where the target scenario is for providing a wireless broadband service in urban and suburban areas. The first business case entitled “Spectrum Sharing” is an extended version of the business case proposed in [2], with more extensive research behind the business case assumptions and parameters, updated results, more details about the model used and the business case ecosystem. This paper also study a second business case entitled “Spectrum Broker” which is based around the concept of an entity that deploys, builds and operates a sensor network and sells either sensing information or information on spectrum opportunities to one or more CR operators. The concept of a spectrum broker has previously been proposed and studied in [3] and [4], but to the authors best knowledge there does not exists any business case proposal for this concept. The third business case proposal entitled “New Entrant” study the potential of a new entrant without existing infrastructure or frequency licenses, that uses a sensor network aided CR system to offer a nomadic mobile broadband service.

The rest of this paper is organized as follows: An overview of the Sensor Network Aided CR (SENDORA) system is given in Section II. The SENDORA ecosystem is described in Section III and the model for analysis and ecosystem evaluation is described in Section IV. Assumptions behind the business cases are described in detail in Section V before the results for the three business cases are presented in Section VI, VII and VIII. The paper is concluded in Section IX.

II. OVERVIEW OF THE SENSOR NETWORK AIDED COGNITIVE RADIO SYSTEM

A. System Overview

The SENDORA technology utilizes wireless sensor networks (WSNs) to support the coexistence of licensed and unlicensed wireless users in an area, and the SENDORA scenario is constituted by three main networks; the primary network, the secondary network and the sensor network. The general architecture of the SENDORA system is depicted in Figure 1, where the network of cognitive users, called the secondary network, first communicates with the wireless sensor network. The wireless sensor network monitors the

This paper presents results of a study conducted within the EU FP7 project SENDORA [1] for a sensor network aided cognitive radio system.
spectrum usage, and is thus aware of the spectrum holes that are currently available and can potentially be exploited by the secondary network. This information is provided back to the secondary network. The secondary users are then able to communicate without causing harmful interference to the licensed network, called the primary network.

The sensor network aided approach will significantly improve the system’s ability to detect primary users compared to CR solutions based only on sensing performed by terminals. The sensor network will consist of an externally deployed sensor network and possibly sensing capabilities embedded in user terminals. The external sensor network makes it possible to guarantee that primary users will be detected with a specified probability regardless of the number of CRs present in the area. Additionally, embedded sensing in terminals can enhance system performance by providing more local sensing information from the areas where the CR users are located and sensing will be improved as the number of cognitive users grows. The sensor network can also be used to measure the interference generated by the CR system. This can be used to control the interference generated to ensure both protection of primary systems and optimal use of spectrum holes.

The target scenario for the SENDORA systems is for providing a nomadic wireless broadband service in urban and suburban areas. The systems will be best suited to provide non-real-time services like web browsing and video downloading. Real-time services like telephony and streaming can be provided occasionally, but the operator will usually not be able to give strict quality guarantees for such services.

B. System Architecture

The system architecture depicted in Figure 1 consists of three parts: the communication architecture and the sensing architecture which are connected together by the fusion centre.

1) Communication Architecture

The fusion centre functionally connects the sensor network and the communication network and acts as an aggregation point for the data from the sensors in the sensor network. Based on the sensor data received, the fusion centre estimates the spectrum usage in the geographical area covered by the sensor network. A CR network might have more than one fusion centre which will communicate with each other and share information about the spectrum situation in their areas and their own network’s usage of spectrum resources.

III. SENDORA ECOSYSTEM

Ecosystem considerations for the sensor network aided CR system are presented in this section, with the chosen scenario: “Nomadic broadband in urban and suburban areas” as the basis for these considerations. The word “ecosystem” in this context mean business modeling [5] including the roles of the actors, relations (like partnership) between the actors, cost and revenue structures and money flows between the actors. Specific business cases can then be used to quantify the value of different ecosystem options. For related work; Chapin and Lehr.
studied interlinked technical and economic issues associated with markets for DSA-based wireless services in [6].

The studied system is an innovative concept with a long term focus, and therefore the related ecosystem is unproven in real market conditions. There will be several actors (see section III.B), that may not always have the same interests and expectations. The requirement for a successful and functional new ecosystem is that the (main) actors have sufficient incentives to be part of that ecosystem. The most important and sometimes the only incentive, at least for the commercial actors, is simply the money i.e. the economical results for the company in the short and long term.

This ecosystem will include mostly actors, which have economical profit as their main motivation, but it can also include actors like regulators, which can have other motives, like for instance welfare of the society as a whole, fairness and a wish to increase competition in the telecommunication. To create a functional SENDORA ecosystem will be a challenging task with many uncertain aspects.

A. Ecosystem Roles

SENDORA ecosystem will include both traditional roles in the communication business and some new roles specific only for the SENDORA ecosystem. At least the following roles can be foreseen in the ecosystem for the sensor network aided CR in the chosen scenario:

1. End user of the communication applications
2. Owner of the license for the radio spectrum
   - Existing mobile and/or fixed telecom operators
   - TV broadcasters
   - Public authorities (such as police, health care, aviation)
   - Military organizations
3. CR operator that will utilize a radio spectrum licensed to others
   - As in point 2 above
   - New operators
4. Regulatory body
5. Spectrum broker
   - Regulatory body
   - Owner of the license for the radio spectrum
   - Independent third party
6. Owner of the sensor network
7. Hardware and software vendor
   - CR elements
   - Sensor network elements
8. System integrator

There is a clear difference between roles and actors in the ecosystem. One specific real actor (company) can have several roles in the SENDORA ecosystem. As an example, an existing mobile operator can simultaneously be a spectrum owner, CR operator, owner of the sensor network and spectrum broker.

B. Ecosystem Actors

The different actors in the future SENDORA ecosystem will have varied motivations why they will be part of this ecosystem. In the sequel follows a discussion of what could be the motivations of different actors.

1) End users of (telecommunication) services

In principle, the normal end user (person) does not care about technology. What matters to the end user is the price and quality of the services provided. The CR or SENDORA system is mostly invisible to the user and has only indirect influence to the user. It can make possible better and more affordable services through technology advancements and increased competition between service providers.

One special user group in the SENDORA ecosystem could be technologically advanced users, that could remove the need for a network operator by having own ad-hoc networks to provide nomadic broadband for a limited user group. This requires advanced technical skills and also coordination (regarding terminals, software etc) between the users.

2) Existing (mobile) operators

Mobile operators can have many roles (spectrum owner, CR operator, broker, owner of the sensor network) in the SENDORA ecosystem. They can have defensive motives (e.g. to hinder that cognitive operation disturbs their primary operation, to protect their valuable assets in already acquired spectrum licenses), but they can also have offensive motives (e.g. earning money on SENDORA spectrum trading, improving their own operation by SENDORA system, being themselves CR operators in new areas).

3) TV broadcasters

TV broadcasters are important spectrum owners, and they will avoid that the new systems disturb their TV distribution. As for other spectrum owners, SENDORA spectrum trading is an earning opportunity for the TV broadcasters.

4) Public authorities

Public authorities (e.g. police, fire brigades, health care, aviation and military) are on the other hand spectrum owners, but they could also be CR operators. For them one important application could be high quality ad hoc networks during large accidents or military actions.

5) New operators

CR operation is one possibility for new operators to enter the market. In the mobile business until now the ownership of the spectrum license has been crucial and expensive part of the business model. The potential new operators are clearly interested in getting a reasonable priced access to spectrum by the SENDORA system.

6) Regulatory body

Regulatory bodies have interest to all technologies that can improve the utilization of the radio spectrum. The spectrum relevant for telecommunication purposes is a limited and therefore expensive resource. The opportunistic use of radio spectrum is not yet scheduled in Europe (it has been allowed in TV white spaces by FCC in the US [7]), but it may be needed soon to open some bands to cognitive operation considering the future need for bandwidth. Today’s approach consists in dividing the spectrum into small pieces, each for a specific purpose and the applications use their spectrum to a limited extent, which leads to the unwanted situation of under-
utilization of this scarce resource. Regulation authorities recognize that this approach is reaching its limits.

One of the key issues for the regulation is how to control interference among systems. In the SENDORA ecosystem, the regulation may be provided interference measurement means thanks to the WSN approach. The WSN could even be owned by the regulator.

7) Vendor

Vendors are also key actors in the ecosystem. Base stations (BSs) and terminals require some new capabilities to allow CR operation, and especially WSN-aided CR operation. In particular, hardware platforms must be flexible enough to support communications in several frequency bands and will be based on a Software Radio approach. In the ecosystem, the vendors must be given the opportunity to sell a sufficient quantity of stations and terminals with enough margins.

C. Examples of SENDORA ecosystems

SENDOORA ecosystems can have different grade of complexity. The simplest SENDORA “ecosystem” is the case where one actor, such as a mobile operator with a variety of spectrum resources, will use CR for better utilization of its own spectrum to provide new services. An extension of this is a “spectrum sharing” case (see section VI), where spectrum owners form a joint venture that gets rights to use the “unused” spectrum of all those spectrum owners in a cognitive way. Minimal coordination and interaction with other actors is needed for such ecosystems.

The more complete SENDORA ecosystem can include spectrum trading between the spectrum owners and the new cognitive operators. This trading can be replaced by regulatory decisions to regulate the access to the spectrum. One possible important new role in this kind of ecosystem will be the broker role, often a regulatory body or an independent third party, that will ensure fairness in the interactions. This kind of ecosystem is more complicated to create, because it may require coordination, trust and interaction between actors, which even may have conflicting motivations for participating. Detailed rules governing the CR operations have to be developed. The broker (Section VII) and new entrant (Section VIII) cases are the first attempts to analyze these aspects.

IV. BUSINESS CASE ANALYSIS AND ECOSYSTEM EVALUATIONS

SENDOORA is an innovative concept and much research and development remains before commercial applications will appear. Therefore the input data to the SENDORA business cases is uncertain and the results from the business case calculations can only give indications, not yet definite answer or strong conclusions. The main value of SENDORA business case calculations is to identify critical aspects for SENDORA profitability, so that technical R&D work can focus on them.

The traditional cash flow analysis will be used to get an indication of the profitability. The cash flow means income (revenues) subtracted by cost (investments and operational costs) for a given time period. Due to large uncertainties the cash flow analysis must be enhanced with sensitivity analysis. Sensitivity analysis is done by changing the value of one (critical) input parameter and showing how the economical results are changing.

Several economical concepts are used in the business case analyses in this document. These are summarized below:

- **ARPU (Average Revenue Per User)**
- **CAPEX (Capital expenditures)** is expenditures associated with the implementation or extension of fixed assets. There is a residual value associated to these expenses. Investment is often used as an identical term to CAPEX.
- **OPEX (Operational expenditures)** is defined as expenditures necessary for running the business or the equipment, indispensable to keep the services active and running. Once made, these expenses have no residual value.
- **EBITDA (Earnings before interests, taxes, depreciation and amortization)** = Revenues – OPEX. This measure is often used to estimate the operational efficiency.
- **NPV (Net present value)** is the sum of a series of cash flows (revenues subtracted by costs), when discounted to the present value:

\[
NPV = \sum_{t=1}^{n} \frac{A_t}{(1 + p)^t}
\]

where \(p\) is the annual discount rate, \(A_t\) the amounts of years that it takes to give NPV = 0. The higher the IRR is, the better the project is. Assuming all other factors are equal among various projects, the project with the highest IRR would probably be considered the best.

**Payback period** is the amounts of years that it takes to have the accumulated revenues equal the accumulated costs (CAPEX and OPEX).

These concepts are not necessarily always unambiguous; there can be slight variations and different interpretations. More information about economical terms can be found in [6].

V. BUSINESS CASE ASSUMPTIONS

A. General assumptions

The business case is calculated for a hypothetical western European city with 1 million inhabitants and with an area of 200 km². The city has a downtown area which covers 50 km². All calculations will be made for this city, but can with some effort be scaled up and down for larger and smaller cities.

The studied city is assumed to have a well developed telecommunication market. This means a high penetration of both mobile (voice, data and broadband) and fixed telecommunication services and also TV services. A working competition environment with several network owners and service providers is assumed.
The commercial realization of SENDORA technologies lies some years ahead. To allow for this, the study period is assumed to be from 2015 to 2020. This adds some more challenges to the study, since the technological developments and other development related to the telecom industry in the years from now (2010) to 2015 must be anticipated.

A traditional cash flow analysis will be used to get an indication of the profitability. The discount rate used in the calculations is 10%. Due to large uncertainties the cash flow analysis will be enhanced with sensitivity analysis. The basis target scenario business case calculation can be described with:

- **Service provided**: Nomadic broadband in urban and suburban areas, mostly non-real time services (best effort).
- **Sensing architecture**: Both an externally deployed network of fixed sensors and embedded sensing capability in the terminals (integrated sensors).
- **Communication architecture**: The communication architecture consists of a centralized network of BSs through which the terminals can get Internet access, complemented by terminals communicating directly between each other forming local ad hoc networks. This study will only consider the centralized part of the architecture, i.e. communication via BSs. There may be local ad hoc networks, but these are assumed not to affect the business case.

Deployment of the CR network in the city will be done in three stages. The network for the downtown area (50 km²) will be deployed in 2015, and the network in the suburban area in 2016 (75 km²) and 2017 (75 km²).

### B. Revenue Assumptions

1) **Revenues From Subscriptions**

To estimate the subscription fee that can be charged for the SENDORA service, we will compare to the corresponding fee for mobile broadband services. The main use of both the SENDORA service and the mobile broadband service will be for providing Internet connectivity for different types of terminals. However, the SENDORA service will have inferior QoS support and will not support mobility. On the other hand, the SENDORA service can offer higher peak capacities when sufficient spectrum is available and better coverage (including indoor coverage) since it can use a larger range of frequencies. But all in all, the SENDORA service is clearly a somewhat lower grade service than mobile broadband, and hence its subscription rates should also be somewhat lower.

To find what a typical mobile broadband subscription rate could be, a simple survey of prices offered was done in a set of European countries in June 2010. The minimum and maximum subscription rates are 23.90 and 38.00 € / month respectively. The average rate is 31.9 € / month.

We will assume that there is a moderate yearly reduction of the subscription fee. This reflects the trend that the operators often choose to increase the performance parameters such as the throughput and data allowance, and keep the fees fixed. However some reduction should still be expected due to the competition. We will assume an average yearly reduction of the subscription fees of 2%. We thus expect the average mobile broadband subscription fee to be about 28.7€ in 2015.

To determine exactly how much lower the subscription rate for the SENDORA service will be, is of course very difficult. Hence any estimate will be very uncertain. We have chosen to assume a subscription rate for the SENDORA service of 20 € / month in 2015. This is about 30% lower than the expected average mobile broadband subscription fee. In reality there are important dependencies, like price elasticity between the mobile/nomadic broadband services from the other operators and the nomadic broadband services from the joint venture (i.e. if one operator increase its tariffs, it will get less users because of competition). These aspects are complicated and not taken into account in the business case calculations.

As the model for the number of customers we will assume that the joint venture has 10,000 subscribers in 2015 (end of the year) and 100,000 subscribers in 2020. Since we assume that the city has 1 million inhabitants, this corresponds to assuming that 10% of the city’s population are subscribers of the joint venture operator in 2020. It is assumed that the number of subscribers as a function of time follows an S-curve often referred to as a generalized logistic curve or Richard’s curve. The number of subscribers at the end of each year in the study period is given in Table 1.

<table>
<thead>
<tr>
<th>Year</th>
<th>#subscribers</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>10 000</td>
</tr>
<tr>
<td>2016</td>
<td>25 785</td>
</tr>
<tr>
<td>2017</td>
<td>40 894</td>
</tr>
<tr>
<td>2018</td>
<td>59 951</td>
</tr>
<tr>
<td>2019</td>
<td>80 654</td>
</tr>
<tr>
<td>2020</td>
<td>100 000</td>
</tr>
</tbody>
</table>

2) **Revenues from selling sensor information**

The joint venture can also get income from selling sensor information to for instance other companies, the regulator or public authorities. Some examples of data that can be sold are:

- Electromagnetic field strength measurements to monitor the exposure people in the area experience to such radiation.
- Measurements of pollution level (e.g. to detect illegal emissions from factories in the area)
- Weather data (temperature, air pressure, wind speed, precipitation, etc.)
- Spectrum holes (not utilized by the joint venture)

The addition of such measurement capabilities can increase the price of the sensors. We will not assume any income from selling sensor information in the studied business cases.

### C. Sensor network related assumptions

The sensor network related assumptions consists of the costs related to purchasing and operating the fixed sensor network and the fusion centre, and the possible costs for subsidizing user terminals with sensing capabilities. To calculate the CAPEX and OPEX for the fixed sensor network, it is necessary to know the number of sensors needed or equivalently the required fixed sensor density.

1) **Required sensor density**

One of the most important parameters for SENDORA systems is the required fixed sensor density. This parameter again depends on other parameters, like what sensing technology is used, what primary systems that must be detected...
and the regulatory requirements. Sensor density was especially studied in [10].

The fixed sensor density used in the business cases is based on results for a case study with LTE as the primary system. The parameter input set for the study is given in Table 2. Two input parameter sets are considered since the exact value of many of the input parameters is not known. The strict parameter set includes parameters that make sensing more challenging, while the loose parameter set relaxes some physical constraints and requirements.

**TABLE 2. PARAMETER INPUT SET FOR THE LTE CASE STUDY**

<table>
<thead>
<tr>
<th>Case Study</th>
<th>LTE Strict</th>
<th>LTE Loose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Model Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Path-loss exponent</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>Lognormal zero-mean shadowing</td>
<td>5dB</td>
<td>5dB</td>
</tr>
<tr>
<td>Tot. AWGN on sensed band</td>
<td>-96dBm</td>
<td>-100dBm</td>
</tr>
<tr>
<td>Primary System Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal Bandwidth</td>
<td>5MHz</td>
<td>5MHz</td>
</tr>
<tr>
<td>Signal Power</td>
<td>24dBm</td>
<td>24dBm</td>
</tr>
<tr>
<td>Max. prob. of interference</td>
<td>$10^{-6}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Interference radius</td>
<td>400 meter</td>
<td>300 meter</td>
</tr>
<tr>
<td>Design Parameters</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensing Bandwidth Unit</td>
<td>200kHz</td>
<td>200kHz</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>400kHz</td>
<td>400kHz</td>
</tr>
</tbody>
</table>

The following measures are defined:

- **Cognitive capacity**: is the portion of narrow band bandwidth one cognitive user receives. For example, a cognitive capacity of 50% means 100 kHz bandwidth per cognitive user.
- **Probability of interference**: the probability that a channel used by the primary system is miss-detected and allocated for a cognitive user.

Furthermore, the following description of the networking environment applies:

- Primary system load is characterized by the probability that a channel is used.
- All sensors sense the same set of channels.
- Channel allocation in the secondary system is modeled by the fair sharing of channels that are detected free.
- Interference control is characterized by the interference radius, which is the minimum distance of primary and secondary transmitters, such as no primary receiver experiences interference, assuming fixed transmission power at both the primary and the secondary transmitters. Interference happens if a secondary transmitter within this radius transmits on the channel that is used by the primary system.

The fixed sensors density required depends on density of user terminals. As the density of user terminals increase, they will provide more sensing information through their integrated sensing capability. But since capacity demand also increases with increasing user terminal density, more accurate sensing data is required. The obtained results for the strict and loose LTE scenarios are given in Table 3 and Table 4 respectively. To optimize the business case the number of sensor sites should be minimized. As can be seen from Table 3 and Table 4, minimum number of fixed sensors occurs when the cognitive user density is about 75 and 35 users/km² respectively.

<table>
<thead>
<tr>
<th>Secondary User Density</th>
<th>Fixed sensor density</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[users/km²]</td>
<td>[sensors/km²]</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>450</td>
<td></td>
</tr>
</tbody>
</table>

In order to minimize the required fixed sensor density, the users can be divided into groups using different and disjoint sets of frequencies. The number of users in each group should be optimized such that the number of fixed sensor sites is minimized. For example, using the strict LTE results, if the number of users is 300 they can be divided into 4 groups each having 75 users. Each group uses a different set of frequencies, so they can be seen as 4 independent groups operating in parallel. Hence, from Table 3 it can be seen that it is sufficient to have 75 fixed sensor sites. However, at each site there must be sufficient sensing capacity to cover all 4 sets of frequencies.

Figure 2 shows for the strict LTE case the minimum density of fixed sensor sites as a function of the secondary user density for a targeted cognitive capacity of 10%. The relationship between user density and fixed sensor density has been calculated from Table 3 by using linear interpolation. The corresponding curve for the loose LTE case is shown in Figure 3. As can be seen from Figure 2, the required fixed sensor density for the strict LTE case is highest when the secondary user density is low. At each multiple of 75 users/km², the required fixed sensor density takes its minimum value of 75 sensors/km². In between these multiples, the fixed sensor density has local maxima which become lower as the secondary user density increases.

The number of cognitive terminals in an area varies randomly. The number shows both short term variations from one minute to the next as users enter and leave the area, medium term variations from high values during peak hours to low values during low periods and long term variations from low values right after the network has been deployed to higher numbers as the operator gets more customers. The dimensioning of the fixed sensor network must be done in such a way that primary systems are given the required protection at all times. Hence, generally it is the maximum values shown in Figure 2 and Figure 3 that should be considered.
The difference between the required fixed sensor density for the strict and loose LTE case is very large, which is partly due to the very different maximum interference probability requirements ($10^{-6}$ versus $10^{-1}$). These requirements can be specified by the regulator or the cognitive operator can make an agreement on this depending on the situation. Since the probability of interference requirements probably will be set in an agreement between the owners of the joint venture, it should be expected that these requirements will be somewhat lower in this case than when the regulator specifies the requirements. Hence the required number of fixed sensors is expected to be somewhat lower in this case than when the regulator specifies the requirements.

The complexity of a fixed sensor was estimated to be about the same as that of a Wi-Fi Access Point. In addition it must be taken into account that these sensors will be placed outdoors and must stand different types of weather conditions. With these inputs a natural assumption is that the price of a fixed sensor will be about the same as the price of an outdoor Wi-Fi Access Point. This price is typical several hundred Euro today.

Taking into account technical development and price reduction expected from now until 2015, we will assume that the price of a fixed sensor is 300€ in 2015 decreasing to 177.1€ in 2020.

4) Fixed Sensor Installation Costs

The fixed sensor installation costs include truck roll, mounting the sensor, connect it to the mains and provide a wired or wireless connection. All fixed sensors in an area should be mounted at the same time to minimize the truck roll expenses. We will assume that one man will mount a sensor in 1 hour on average including the time it takes to drive between the sensor sites, and that the hourly costs for him and the van is 50€ in 2015 decreasing to 45.2€ in 2020.

5) Fixed sensor operational costs

The fixed sensor operational costs cover sensor site rental, power consumption and maintenance.

It is important that the fixed sensors are robust with a very high mean time between failures. Most of the reconfiguration and adjustment of the sensors should be controlled through its wired or wireless sensor network connection. If a maintenance visit is required once every 3 years (36 months) on average and the cost of a maintenance visit is 50€, the average monthly costs would be 1.4€/month/sensor.

We assume that a fixed sensor consumes 10W at average, giving a monthly electricity consumption of 7.2kWh. With a tariff of 0.30€/kWh, the monthly electricity costs is about 2.2€/sensor/month.

The average fixed sensor site rental cost is more difficult to estimate. The sensors will be relatively small of size similar to an outdoor Wi-Fi access point. They will typically be placed where there is an easy access to the mains, for example at top of lamp posts. We estimate the average sensor site rental to be in the order of 10€/month/sensor. Based on these considerations we assume that the total fixed sensor operational costs is 15 €/month/sensor in 2015 decreasing to 13.6€ in 2020.

6) Fusion centre costs

The fusion centre costs consist of the purchasing, installation and operational costs. We assume that one fusion centre is sufficient and that this is located at the joint ventures office so that the place rental, electricity costs and maintenance are included in the company’s general operating costs. The fusion centre will consist of a powerful computer with high communication capacity. We will assume that the price for the fusion centre is 150,000 € and installation costs are 10,000 €.

7) Subsidization of user terminals

Having sensing capabilities in the terminals can reduce the need for fixed sensors. Hence, it can be a good idea for a SENDORA operator to subsidize user terminals with sensing capability to reduce costs for the fixed sensor network. However, we will not consider such subsidies in the business case calculations.

D. Cognitive radio access related assumptions

The CR access related assumptions consists of the costs for installing and operating the CR BSs and for establishing new BSs sites.
1) Number of cognitive base stations
The geographical density of BSs for the SENDORA systems is assumed to be similar to that for mobile broadband networks. Hence, a SENDORA operator that can exploit BSs sites of a mobile broadband operator as in the joint venture case can often get the required coverage and capacity without having to establish any new BS sites.

The number of cognitive BSs required in the targeted city is assumed to increase from 50 the first year to 450 after 5 years. These numbers are based on operator experience from deploying 3G cellular networks.

<table>
<thead>
<tr>
<th>Year</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>#BS</td>
<td>50</td>
<td>175</td>
<td>250</td>
<td>350</td>
<td>400</td>
<td>450</td>
</tr>
</tbody>
</table>

As the base case it is assumed that the operator will get sufficient capacity and coverage by sharing infrastructure with the operators behind the joint venture, such that it is not necessary to establish new BS sites. Establishment of new BS sites will however be considered in the sensitivity analysis.

2) Costs for installation of cognitive functionality in BSs
It is assumed that at least one of the owners of the joint venture is a cellular operator having an infrastructure of BSs and backhaul in the area. The joint venture operator can outsource cognitive BS functionality to the cellular operators. The cellular operators can update their BSs, which by 2015 is based on software defined radio solutions. It is assumed that the costs for updating/upgrading a BS with cognitive functionalities is 5,000€ in 2015 decreasing to 2,953€ in 2020.

3) Cost for establishing new sites
If updating/upgrading existing BS with cognitive functionality does not give the required coverage and capacity, it will be necessary for the SENDORA operator to establish new sites. The cost for establishing a site consists of costs for identifying and acquiring the site, building the antennas, housing and providing it with power and backhaul.

It will be assumed that the costs for establishing a new SENDORA BS site is comparable to that of establishing a new 3G cellular BS site. Based on operators’ experience we will estimate this cost to be 60,000€. In the base case it is assumed that no new sites are required.

4) Costs for cognitive base station maintenance, backhaul rental and site rental
The costs associated with renting the BS site, renting backhaul capacity and maintaining the BS is assumed to be 1,000€/month/site in 2015, decreasing to 904€/month/site in 2020.

5) General OPEX
This OPEX reflects the general efficiency of the joint venture and covers e.g. customer acquisition (sales and marketing) costs and general operation of the company. Its value is highly uncertain and difficult to benchmark due to different accounting principles in different companies and countries. It is mostly independent of the SENDORA concept. The value used for general OPEX is 8€/subscriber/month in 2015 decreasing to 5.6€ in 2020.

VI. BUSINESS CASE 1: SPECTRUM SHARING
The main idea behind this business case illustrated in Figure 4 is that several spectrum owners establish a joint venture and this joint venture gets the rights to use the “unused” spectrum resources of all those spectrum owners in a cognitive way based on the SENDORA concept.

Figure 4. A number of spectrum owners form a joint venture operator that gets the rights to use the “unused” spectrum resources of all those spectrum owners in a cognitive way based on the SENDORA concept.

The joint venture will build a fixed sensor network and will provide a cognitive nomadic broadband service in the “unused” spectrum. The business case is calculated from the point of view of this joint venture where the mother companies establish the joint venture and hope to get the invested money back by receiving dividends from the joint venture. The success criterion could be for example that the pay-back period (time until accumulated cash flow turns positive) is less than five years.

The spectrum owners can be of different types, for example companies having bought spectrum just as an investment, cellular operators and broadcast operators. However, it is assumed that at least one of the spectrum owners is a cellular operator having an infrastructure, including backhaul and BS, in the area. Then the joint venture can reuse this infrastructure by leasing CR access functionality and backhaul capacity from the cellular operator.

Due to the close connection between the joint venture and the owners of the spectrum used, it can be expected that the maximum levels of interference accepted by the spectrum owners can be somewhat relaxed compared to the case where the spectrum owners do not get any economical benefits for the secondary use of their spectrum.

The joint venture represents a practical way of dividing the incomes and expenses of the CR network between the spectrum owners. The composition of the joint venture is very important and should ensure both that the CR network get access to sufficient spectrum resources and that there are little need to build new infrastructure (e.g. BS sites).

From a strategic point of view spectrum sharing is not much used today. However, it can be seen as a natural extension of infrastructure sharing, which used to be limited to sharing of non-electronic infrastructure (e.g. antenna mast) but has now been extended to sharing of electronic infrastructure.
Sharing important network elements like BSs was almost unthinkable from a strategic point of view only a few years ago but is now becoming increasingly popular.

From a regulatory point of view, this business case is probably one of the easiest to implement since the joint venture operator uses only the owning companies’ spectrum. Hence, the main regulation of acceptable interference can be done among the joint venture owners and little coordination is required with external spectrum owners. If technology neutral regulations applies to for the frequencies used by the joint venture operator, there should be no or little need for coordination and for getting permissions from the regulator.

A. Base case

The business case calculation was first done with the assumptions given and explained in the previous sections. By combining costs (CAPEX and OPEX) with revenues the yearly cash flows and standard profitability indicators, like NPV, IRR and pay-back period, was calculated. For the definition of these, please refer to section IV.

It is important to emphasize that SENDORA is an innovative concept and much research remains before it becomes a mature technology. This means that many basic assumptions in the business case calculation will remain uncertain for a long time. Hence, the results will not give definite answers but only indications to whether it is possible to make business utilizing the SENDORA concept.

B. Sensitivity analysis

As already underlined, the input assumptions for this kind of future oriented business case are uncertain. Therefore it is interesting to see how changes of the value of different parameters affect the results.

There are many aspects, which are independent of the SENDORA concept, but have crucial influence on the profitability. Examples of these are the operational efficiency of the joint venture (influencing OPEX) and the competition situations (influencing ARPU and number of customers). We do not evaluate these aspects further, except doing sensitivity analysis on ARPU, but concentrate on aspects where the SENDORA concept has crucial influence.

Sensitivity analysis is done here by changing the value of one critical input parameter and showing how the economical results are changing. All other input parameters are as in the “Base case”. NPV is used as the indicator of profitability.

1) Fixed sensor density

Since the novel idea in SENDORA is to combine CR with sensor networks, the required number of fixed sensor per km² is one of the most crucial parameters for the SENDORA approach. Also, as explained in Section V.C, there are large uncertainties associated with this number. For example is it uncertain what probability of interference the spectrum owners will accept.

Table 6 lists NPV for different values of the fixed sensor density. As can be seen, the business case is very sensitive to changes in this parameter. Just by increasing the sensor density from 65 to 72 sensors/km², which is a very small change from a technical perspective, the NPV starts getting negative.

In section V.C the fixed sensor density for two cases, strict LTE and loose LTE, were presented. The required sensor densities ranged from 10.5 sensors/km² in the loose LTE case to 120 sensors/km² in the strict LTE case. Clearly, these values give extremely different results for the business case.

The fixed sensor density requirement can for example be reduced by employing more advanced sensing techniques or complementing sensing data with other information (e.g. from the primary operators). Also, this analysis shows that it is important that regulators and spectrum owners have this in mind when deciding on the interference probability limits.

2) Fixed sensor price

Sensitivity analysis of the fixed sensor price is interesting since it concerns the sensor network, which is central to the SENDORA concept. The price for a fixed sensor is uncertain since such equipment has not been produced yet, but is still researched on and exists as prototypes at best. The price used in the base case was derived by comparing it to outdoor Wi-Fi access points, which is expected to have similar complexity and enclosure requirements.

Table 7 lists NPV for different values of the fixed sensor price. As can be seen, the business case is very sensitive to changes in this parameter. Just by increasing the sensor price from 50 Euros to 1000 Euros, which is a very small change from a technical perspective, the NPV starts getting negative.

Figure 5 shows the accumulated cash flow for the study period 2015-2020 with the assumptions given in the previous sections. NPV for the study period 2015-2020 is 1.36 million Euros, IRR is 16 % and the pay-back period is about 5 years.

The accumulated cash flow and the associated economical results are quite similar to many others telecommunication infrastructure projects. That means that it will be tough and a long-term business case, where the operator (joint venture) must be patient and have financial strength with long term financing to wait a longer period for the return on investment.

Table 6 NPV sensitivity for changes to the fixed sensor density

<table>
<thead>
<tr>
<th># fixed sensors per km²</th>
<th>NPV [MEuro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>11.44</td>
</tr>
<tr>
<td>30</td>
<td>7.77</td>
</tr>
<tr>
<td>65</td>
<td>1.36</td>
</tr>
<tr>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>120</td>
<td>-8.72</td>
</tr>
</tbody>
</table>

Table 7 NPV sensitivity for changes to fixed sensor price

<table>
<thead>
<tr>
<th>Fixed sensor price [Euro]</th>
<th>NPV [MEuro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3.98</td>
</tr>
<tr>
<td>150</td>
<td>2.93</td>
</tr>
<tr>
<td>300</td>
<td>1.36</td>
</tr>
<tr>
<td>430</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>-0.74</td>
</tr>
<tr>
<td>700</td>
<td>-2.84</td>
</tr>
<tr>
<td>1000</td>
<td>-5.99</td>
</tr>
</tbody>
</table>
Table 7 lists the NPV for different values of the fixed sensor price. It can be seen that the fixed sensor price must be raised from 300€ to 430€ (+43%) before the NPV gets negative. A similar moderate change in the NPV can be seen if the price is halved from the base case value.

It can be concluded that the fixed sensor price is not the most sensitive parameter, but still important. It will be a challenge to meet the cost assumptions used in the base case, but moderate deviations (say ±10%) from this is not critical for the business case.

3) Fixed sensor OPEX

The operating cost of fixed sensors (electricity, maintenance, sensor site rental) is a very uncertain parameter, especially the sensor site rental component. It is important to determine the sensitivity of the business case for this parameter to assess the importance of fixed sensor power consumption, durability and space requirements.

Table 8 lists NPV for different values of the fixed sensor OPEX. It can be seen that if the OPEX is increased from 15 to 17.5€/month/sensor, the NPV starts getting negative. This is a small increase (16%); much smaller than the uncertainty of this parameter. Hence, this is a parameter that a CR operator must have under control before deciding to build such a network.

The high sensitivity for this parameter shows that it is critical that the fixed sensor power consumption is low and that the mean time between failures is long. The first requirement can be achieved by exploiting the appropriate integrated circuit technologies, while the second requirement can be met by ensuring that the sensors have high quality and integrate “self-healing” capabilities in the units.

4) Share of new sites

In this business case it is assumed that at least one of the spectrum owners owning the joint venture is a cellular operator, and that the joint venture operator can exploit the existing infrastructure (e.g. sites, BSs and backhaul). However, it might turn out that it is necessary to establish some new sites in addition to the existing ones in order to get the wanted coverage and capacity.

In the base case it is assumed that no new sites are built. In a real situation this assumption might turn out to be optimistic, and it is hence interesting to see how the business case is affected if different shares of the sites are new sites.

Table 9 lists the NPV for different shares of new sites. It can be seen that the NPV starts getting negative if the share of new sites exceeds 6%. If a large part of the sites are new sites, the business case will be strongly negative. Hence, it is important that new sites are avoided. However, if the share of new sites can be limited to a few percent, the business case will be only moderately affected.

An important parameter for the business case is the subscription fee, also called the ARPU. This is a parameter that depends mostly on what price level that is formed in the market for wireless broadband services, and is therefore not directly related to the SENDORA concept. However, the ARPU depends on how much customers grade the service provided by the SENDORA network. If the joint venture operator is able to provide a service which is better than assumed here, the ARPU will be higher than assumed in the base case. If the grade of the service provided is lower than assumed, the ARPU will be lower than in the base case.

Table 10 lists the NPV for different values of the ARPU. It can be seen that the ARPU is a very critical parameter for the business case. The NPV starts getting negative after a reduction of the ARPU with only 3%. Larger changes of the ARPU give dramatic changes of the NPV.

The ARPU assumption used in the base case was based on a comparison with current mobile broadband subscription fees. Since it is uncertain how much lower the subscription fee for a SENDORA service will be, this assumption is much more than a few percent uncertain. This results shows that it is of crucial importance to be able to offer a service that is preferably better, or at least not much worse, than that of mobile broadband services with respect to average and peak capacity, coverage, delay, QoS, etc.

VII. BUSINESS CASE 2: SPECTRUM BROKER

This business case will be calculated from the point of view of a spectrum broker. The spectrum broker is an entity that deploys (builds and operates) a sensor network and sells either sensing information or information on spectrum usage opportunities to one or more CR operators. It is assumed that the spectrum broker is only charging money to cover its expenses, that is it is assumed that its revenues should be such that the broker will have NPV = 0 for the study period 2015-2020 for building and operating the fixed sensor network. This non-profit broker could be the regulator or an entity set up by the government or local authorities.

This business case scenario is more challenging than the previous business case from a regulatory point of view. CR operation must be allowed in the spectrum used and there must be sufficient amounts of such spectrum available to allow a
small number of CR operators to offer an attractive service with these spectrum resources. The regulatory process for opening frequency bands for cognitive operation can be complex and take long time, where multiple stakeholders are consulted and detailed rules governing the CR operation have to be developed.

It is assumed that the spectrum broker or the CR operators will not pay anything to the owners of the spectrum. Since the spectrum owners are not part of this specific SENDORA ecosystem and they will not get any compensation when others are using their spectrum, it is fair to assume that they should not experience any noticeable interference from the cognitive operation. Therefore it is reasonable to assume that there will be stringent requirements for the interference generated into the primary systems. Taking into account the results on the required fixed sensor density presented in section V.C, we will use the strict LTE case as the basis for the assumptions made. Hence, it will be assumed that the spectrum broker must deploy 120 sensors/km² both in the downtown area and the suburban area of the city.

The marginal (additional) OPEX for the broker to handle the relations to the cognitive operators is set to 200,000 €/year.

All other assumptions regarding sensor network establishment and operation are the same as in the first business case. The broker is not a cognitive operator, so all items related to cognitive operation is not included to this case.

This business case will only give one results, and that is how much the broker must charge from the CR operators in order to have NPV=0 for the study period 2015-2020. This number will be an important input to the next business case, which considers a new CR operator that will use information of vacant spectrum from the broker.

Since it takes some time for the broker to build the fixed sensor network, the service it can provide to the CR operators will be reduced in the start. To take this into account we assume that the broker will only charge half of the yearly fee the first year.

The business case calculations shows that the fees the broker must charge from the CR operators using his information are 2,693,000€ in 2015 and 5,386,000€ for each of the remaining years.

VIII. BUSINESS CASE 3: NEW ENTRANT

This business case takes the perspective of a new CR operator that does not have any existing infrastructure or frequency licenses in the area in question. The operator wants to use a SENDORA system to offer a nomadic mobile broadband service.

The new entrant will build a CR access network, both by sharing infrastructure with existing wireless operators in the area and by building new BS sites. The spectrum needed will be borrowed or rented from the spectrum broker addressed in Section VII. It is assumed that the spectrum broker has deployed a sensor network and all related infrastructure, so the operator does not have to deploy a sensor network itself. However, the cognitive terminals will have sensing capability that the operator might use to improve the quality and resolution of the information received from the broker.

The business case of a new SENDORA operator is somewhat similar to a corresponding business case of a new mobile broadband operator, e.g. a new LTE operator. The difference is that a new mobile broadband operator has to acquire a spectrum license, while the SENDORA operator will base its operation on borrowed or rented spectrum.

All revenue assumptions (number of customers and ARPU) for this business case are the same as for the spectrum sharing business case presented in section VI. The main difference is that the new entrant will not have to build and operate a sensor network as the joint venture operator does, but it can utilize the sensor network information either for free (base case for new entrant) or by paying to the broker an annual fee (section VII). When building and operating the cognitive network we assume that the new entrant in some aspects will have higher costs than the joint venture:

- The SENDORA operator has to establish new BS sites for 20% of the BSs needed (the total number of BSs is the same as in the joint venture case, see Table 5). It is assumed that it costs 60,000 € to establish a new site.
- For the cognitive functionalities in the BSs 10,000 € (decreasing to 5,905 € in 2020) is assumed for equipping it with the needed CR BS components (antennas, modems, amplifiers, etc.). In the joint venture case a lower value (5,000€) is used.
- The new CR operator has to pay a 50% higher rent for sharing infrastructure with the existing operators in the area than in the spectrum sharing business case from section VI. It is assumed that the new entrant must pay a rent to other operators for sharing the BS site, maintenance expenses and backhaul sharing of 1,500 €/month/BS site decreasing to 1,356 € in 2020.

As the base case we will assume that the new entrant do not have to pay anything for the spectrum. This means that the broker must cover the costs of building and operating the sensor network, i.e. this has to be financed by public money. The base case will however be complemented with a sensitivity analysis to assess how the business case is affected if the operator has to pay for using the spectrum. In this case the price that the new cognitive operator has to pay for the spectrum will be derived from the revenue the broker, presented in the business case in section VII, must have in order to get NPV=0 in the study period 2015-2020. This cost might be shared with other CR operators in the area also using sensing information from the broker.

Figure 6 shows accumulated cash flow for the base case. NPV for the study period 2015-2020 is 0.61 million Euro, IRR is 14 % and the pay-pack period is somewhat less than 5 years. This case is even more uncertain than the spectrum sharing case (section VI) and it is quite impossible to state on a general level how profitable a new entrant could be. It depends on local conditions, efficiency of the new entrant, competition situation, timing, regulatory conditions etc. It is important to note that in this base case the new entrant do not have any spectrum costs, which may be an unrealistic assumption even on a longer term.
A sensitivity analysis was performed for the number of new BS sites and for having to pay for the spectrum. Table 11 lists the NPV for different shares of new BS sites.

Table 11: NPV Sensitivity for Changes to the Share of New BS Sites

<table>
<thead>
<tr>
<th>Share of new BS sites</th>
<th>NPV [million Euro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 %</td>
<td>5.00</td>
</tr>
<tr>
<td>20 %</td>
<td>0.61</td>
</tr>
<tr>
<td>40 %</td>
<td>-3.78</td>
</tr>
<tr>
<td>100 %</td>
<td>-16.96</td>
</tr>
</tbody>
</table>

The table shows that the NPV starts getting negative when the share of new sites is increased from 20% to 22%. The uncertainty of how many new sites that is required is typically much larger than this. Hence, this is a parameter that a new entrant must have good control of. If the share of new sites can be reduced below the 20% assumed in the base case, it will affect the business case very positively.

Table 12: NPV When a New Entrant Has to Pay for the Spectrum for Different Numbers of Cognitive Radio Operators in the Area

<table>
<thead>
<tr>
<th># CR operators in the area</th>
<th>NPV [MEuro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-22.50</td>
</tr>
<tr>
<td>2</td>
<td>-10.95</td>
</tr>
<tr>
<td>3</td>
<td>-7.09</td>
</tr>
<tr>
<td>4</td>
<td>-5.17</td>
</tr>
</tbody>
</table>

Table 12 lists NPV when the new entrant has to pay for the spectrum for different numbers of CR operators in the area (when number of operators is 1, the new entrant is the only cognitive operator in the area). It can be seen that the business case is negative if the new entrant has to pay the broker for spectrum information, even if the broker’s costs are divided between 4 operators in the area. Taking into account the market share that has been assumed (100,000 subscribers in 2020 of a population of 1 million), it is even unrealistic to assume that there will be room for four CR operators. Two or three operators are probably the most realistic numbers.

IX. CONCLUSIONS

This paper proposed and evaluated three business case scenarios for deployment of a sensor network aided cognitive radio system studied in a typical European city: a spectrum sharing, a spectrum broker and a new entrant business case scenario. Traditional cash flow analysis was used to get an indication of profitability and sensitivity analysis was used to identify critical parameters of the system due to large uncertainties in the input parameters.

It should be noted in the conclusions that the main value of these business case calculations is the identification of critical aspects for profitability of a sensor network aided CR system, so that future technical R&D work can focus on them. The most critical aspects influencing the profitability were required fixed sensor density and fixed sensor OPEX, where the former depends strongly on what interference limits are set to protect the primary operators. By using different, but all realistic, values for interference limits, it was shown that the required density of fixed sensors could vary by a factor of 10 or more, which indicates that it is important that regulators and spectrum owners consider this when deciding on interference probability limits. The high sensitivity for the fixed sensor OPEX showed that it is critical that the fixed sensor power consumption is low and that the mean time between failures is long.

The spectrum sharing business case is probably one of the best possible cases for the studied system because the joint venture operator has free access to frequency resources of the mother companies, detailed knowledge of the primary systems and good possibilities for sharing infrastructure with the operators owning the spectrum. The new entrant business case scenario is most challenging to make viable, if the new entrant has to pay the broker what he needs for covering his expenses, the business case gets strongly negative even when these expenses are shared with three other cognitive operators also using information from the broker.

ACKNOWLEDGMENT

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REFERENCES