Multilayer sensors for the sensorial radio bubble

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Abstract
We propose to define a volume around cognitive radio equipments, typically terminals, called the ”Sensorial Radio Bubble” or SRB, the diameter of which is at the scale of the sensing possibility of the equipment. The SRB gives communication equipments the ability to explore the radio environment in order to provide knowledge about the spatial and spectral environment, and some context awareness. By analogy to the human sensorial bubble, we assert that this could permit the cognitive radio equipment to plan his coming behavior in order to predict and anticipate its reaction to environment evolution. In this paper we present details of the sensors required in the Sensorial Radio Bubble. The sensors of the SRB may be classified in function of the OSI layers. A simplified three layer model is presented for our purpose. An example of sensor of the lower layer is spectrum hole detection, for the intermediate layers the blind standard recognition sensor is described, and finally for the higher layers a video sensor is presented.

Key words: Sensing system, environment analysis, sensors, cognitive radio, software radio, reconfigurable radio, handover.

1. Introduction

1.1. Cognitive Radio

Cognitive radio relies on Mitola’s work in [1] and [2]. Mitola argues that radio will become more and more autonomous, and thanks to the support of flexible technology (namely SDR) will acquire some self-autonomy to dynamically modify its functionality. As explained in the schematic of Figure 1,
this relies on a cognitive cycle. Figure 1(a) is from [1] and Figure 1(b) is a simplified view of the cycle summarized in three main steps:

- **Observe**: Gathers all the sensing means of a CR,
- **Decide**: Represents all that implies some intelligence including learning, planning decision taking,
- **Adapt**: Reconfigures the radio, designed with SDR principles in order to be as flexible as possible.

In this paper, we address sensing in its largest scale. All information that can help the radio to better adapt its functionality for a given service in a given environment, in other words under given constraints, is worth being taken into account. Then as we make no restriction on the sensors nature, it is possible to draw the general approach exposed in Figure 2. Sensors are classified in function of the OSI layers they correspond to, with a rough division in three layers. Corresponding to the lower layers of the OSI model, we find especially all the sensing information related to the physical layer: propagation, power consumption, coding scheme, etc. At the intermediate level are all information that participate to vertical handovers, or can help to make a standard choice, as a standard detection sensor for instance. The network load of the standards supported by the equipment may be of interest. It also includes the policies concerning the vicinity, the town or the country. The highest layer is especially related to the applications and all that concerns the human interaction with the communicating device. It is related to all that concerns the user, his habits, preferences, policies, profile.
The equipment can be aware of its environment with the help of sensors like microphone, video-camera, bio-sensors, etc. As we are at the early beginning of such technology, it is difficult to foresee all the possibilities. We can think for instance that user’s bio metric information and/or facial recognition will ensure equipment security as shown in the scenario of section 3.1. Video-camera could also be used to indicate if the terminal is outside or inside a building. This may impact propagation features, but also the capability or not to receive GPS signals. Another example could be given in the context of video conferencing, a separation between the face of the speaker and the background could help decreasing the data rate while refreshing slowly the background of the image [4]. At each level, are associated examples of sensors which are able to give information related to this layer (left side of the Figure 2). In addition, at the right side, we identify areas of current research which are more or less connected to CR. As we would like to optimize the overall system, we are obviously also connected to the cross layer adaptation and optimization topics. Note that this classification is also related to three well-known concepts of the literature:

- context aware for higher layers [7],
- inter-operability for intermediate layers [8],
- link adaptation for lower layers [9].
All this may be combined to proceed cross-layer optimizations. This is one of the responsibilities of the cognitive engine in our mind.

However, due to the high financial pressure on spectrum issues, CR is often restricted in the research community to spectrum management aspects as in [10] [5] [11]. Opportunistic spectrum access approaches are explored to increase the global use of the spectrum resources. FCC has been already opening the door for several years, in the TV broadcasting bands [6], and permits to secondary users (e.g. not licensed) to occupy primary users spectrum when available. Most of them indeed are not used in time, space and frequency. This is current commercial state-of-the-art of CR.

More futuristic CR scenarios may also be considered concerning the spectrum management. We may even imagine in the very long term a fully deregulated spectrum access where all radio connections features would be defined on-the-fly: carrier frequency, modulation, data rate, coding scheme, etc. But this means also to overcome regulatory issues in addition to technological challenges.

1.2. Cognitive Radio Equipment

We can derive from the considerations of previous paragraph what should a CR equipment be made of. This is exposed in Figure 3 which schematically represents a CR equipment. The SDR system sub-part is composed
of multiple radio protocol stacks (from the physical to the application layer) executed in a flexible hardware (and corresponding necessary software) platform. Let us just stress that it should include in particular a reconfiguration management software architecture. To make a SDR become a CR, two main parts are to be added: sensing means and a smart sub-system. Sensors in our mind are the combination of electronic devices and algorithms that translate the signals into metrics of interest. For instance we may consider a standard recognition sensor is composed of a RF front-end and a set of processing functions that extract the metric of presence or absence of a set of standards. This information feeds the smart or cognitive engine of the CR equipment that takes decisions accordingly. This means that reconfiguration may be done to adapt the behavior of the equipment to the situation revealed by the sensors of the equipment, or sent by the network, or both of them. Four categories of sensing information worth to be taken into account are given in Figure 3:

- electromagnetic environment: spectrum occupancy, Signal to Noise Ratio (SNR), multi-paths propagation, etc.
- hardware environment: battery level, power consumption, processors using rate, FPGAs gates occupation, etc.
- network environment: telecommunication standards (GSM, UMTS, WiFi, etc.), operators and services available in the vicinity, traffic load on a link, etc.
- user-related environment: position, speed, time of day; user preferences, user profile (access rights, contract, etc.), video and audio sensor (presence detection, voice recognition), etc.

The paper is organized as follows. In section 2, a definition and a presentation of the concept of SRB are provided. To understand the concept of the radio bubble, Section 2.2 gives two analogies. Sections 3, 4 and 5 present the sensors according to the 3 layer of the simplified model of Figure 2. Finally section 6 addresses the conclusions and future evolution of SRB concept.
2. The "sensorial radio bubble" for cognitive radio equipment

2.1. Generalities and Definition

Having in mind the "Human bubble" (see section 2.2.1), the SRB is a multi-dimensional space around a CR equipment, with one dimension for each sensing capability, exactly as the human sensorial bubble gives information to a person of its surrounding environment thanks to the five human senses. We extend, with this SRB concept, the well-known human or animals bubbles to inanimate objects like a CR equipment. From this point of view, this work belongs to the bio-inspired systems domain.

Each dimension (sensor) can be represented with several parameters (such as temperature and time for a thermometer). Therefore associated with each sensor $S_i$ exists a vector of parameters defined as $V_i = [P_{i0}, ..., P_{ij}, ..., P_{iJ-1}]$ for $i = 0, ..., N - 1$ and $j = 0, ..., J - 1$ where $N$ is the total number of sensors and $J$ the number of parameters of the $i$th sensor. It may happen that $V_i$ contains only one parameter $P_{i0}$. One of these parameters may be a range for particular sensors, as the sight distance parameter is a range for the sight sensor.

The SRB provides sensing information to the CR engine (decide function). It will be the responsibility of a CR equipment to be aware and interact with all the pertinent information available in the area that can help the equipment to match its functionality to the global state of its environment. Considering the cognitive cycle, SRB is situated in the Observe step as illustrated in Figure 1. The SRB uses all the 3 layers already defined in Figure 2 (from PHY to application layer) to explore the environment of the equipment. Section 3, 4 and 5 describe it in detail. As it will be illustrated in sections 4 and 5 it could happen that a sensor of one layer uses information providing by sensors of another layer.

Moreover, this work addresses the issue of a double mobility:

- A classical mobility associated with the horizontal handover, in space. The spatial representation of the information given by the SRB will be the result of the combination of all spatial parameters of a sub-set of sensors, and is given through the information provided for instance by the positioning sensor for the SRB center, the Direction Of Arrival sensor for the position of the Base Station, ...
• A spectrum mobility associated with the vertical handover, in frequency. By the same way the spectrum representation of the information given by the SRB will be the result of the combination of all spectrum parameters of a sub-set of sensors. It may be given through the carrier frequency sensor, the channel bandwidth sensor, the standards recognition sensor, etc.

We suggested in [13] to map these two mobilities on two different maps, in order to illustrate and validate our concept of the SRB:

• One is the classical spatial map, which already exists, and in which the equipment is moving.

• We proposed to add a new one: the spectrum map. It contains all the environment information given by the corresponding sensors of the SRB. The way to build this map is described in [13].

These two maps permit to build a model of the CR equipment environment in order to predict its future states. The aim of this model is to apply on it some rules of the ”human bubble” when the human is moving in its own environment and then to derive CR equipment behavior rules when CR equipment is moving in space and in spectrum. The goal of the SRB is to permit the terminal to safely transmit and receive its communications, taking into account overall environment given by the SRB. That is why we also introduce the notion of a ”safety bubble”. The word ”safety” here means that the equipment can ensure the integrity of the transmitted and received information.

How to use this mapping and the resulting model is not discussed in this paper and is still under consideration.

2.2. Analogies

In order to simply expose our concept, we use two analogies. The first and the most important one is the well known psychological and physiological human bubble. The second analogy addresses the human bubble within a car. A spectrum map is defined as a road map, therefore we can translate rules from the latter to the spectrum approach with the objective to secure transmissions the same way as motorists on the road. We already proposed in [13] a traffic code analogy. A close analogy was proposed also in [14]. It has to be stressed that this new spectrum map evolves as soon as the equipment
is moving in the spatial map. So as to better explain this approach, we propose in the following to describe two analogies at the origin of the SRB concept.

2.2.1. The "human bubble" analogy

The well-known physiological and psychological "human bubble" is a virtual space, whose dimensions are given thanks to the human senses. A person knows all information inside his bubble and consequently has a feeling of safety and comfort. In fact, a lot of common expressions use this concept (at least in French) like to be safe in his bubble, to be well in his bubble or, when a person has some social relationship trouble, it is said to be locked in its bubble... It is partly given by the five human senses. The range in a specific dimension is directly dependent on the limitations of the physical senses. For example, human eyes are said to be capable of detecting a range of frequencies between 400 to 700 nm. If frequencies outside this spectrum range are undetectable by humans, it is not the case for some animals. As another example to illustrate this parameter, consider the hearing dimension, it is obvious that this range in the dog bubble will be greater than the one of the human bubble. The safety and comfort impression in a human being bubble is different the night and the day, mainly because the range parameter of the vision dimension is different.

This concept is widely used mainly by the Health and Social domains but also by industry. The human bubble is clearly a concept connected to Health (mainly psychological area). An example could be the Multi-sensory Room for use by students for Learning Disability nursing courses [15]. The room is designed as a multi sensory area usually utilised by people with Learning Disability and others as a form of sensory stimulation to promote relaxation, or stimulation and can be used in conjunction with other therapeutic approaches such as aromatherapy etc.

The room consists of lights, fibre optics, projections, bubble tubes, sound equipment and vibrating equipment that can be operated in a number of ways, to promote stimulation of all senses. Programmes need to be carefully thought out and designed for individuals with specific needs.

Concerning the industry use of the human Bubble concept, the "Fly safety bubble" for safety in avionics seems to be a good example. This "bub-
ble of protection” prevents the pilot from exceeding predetermined limits for various parameters, including bank rate, airspeed and G-loading. For example, the pilot is not allowed to exceed the airplane’s 2.5-G design load, even though a 50% safety factor is built into the structure, suggesting that the airplane is strong enough to pull 3.8 Gs.

In the Cognitive Radio domain, SRB in its side, collects information through many sensors belonging to the three layers previously defined. Some of them analyze the received electromagnetic waves. For example one sensor detects spectrum holes, another one selects, the best (in respect to some criteria) standard for the communication. In addition, as the health condition of a human being may influence his behavior and mood, the internal state of an equipment should be considered (battery level, processor load, etc.).

In the illustration of the human bubble Figure 4, each sense represents a dimension of the human bubble. Each sense itself is defined by a vector of parameters. For instance the perception of wavelength and range could be considered as parameters for human vision. Figure 4 depicts a simplified example having five senses where each sense has three parameters.

We now present the multi-dimension representation of the SRB. It can be visualized as a set of sensors, where each sensor represents a dimension on the SRB space. Like the human analogy each dimension has a set of parameters. This set is put in a vector which characterizes the considered dimension (sensor).
As already said, it could happen that a sensor of one layer uses information providing by sensors of another layer. It is the case, for instance, with the Standard Recognition sensor (SRS) which belongs to the intermediate layer and uses sensors of the physical layer to synthesize the information. An example is given in Figure 5 where we depict the Standard Recognition Sensor (SRS). The SRS itself uses three sensors of the physical layer. The spreading technique FH-DS discrimination sensor, which is one of the sensors of the physical layer used by the SRS, has 3 parameters: time, frequency and energy.

In the human analogy, human beings have information about the environment (light, sound, etc.). The range parameter of a dimension of the human bubble represents the point where he does not have any information about the environment. The range of a specific dimension (sense) can change according the environment. For example the range parameter of the vision dimension can decrease when it is foggy. On the other hand human beings can focus on a specific sense to increase its range parameter. In fact, everybody did the experience to be hardly concentrated on a specific sense and then success to increase the range parameter of the considered dimension (for example to be concentrated on the hearing sense permits to hear far sounds and to take conscious of their existence). The range parameter of a dimension of the SRB can also change according to the environment (obstacles, interferences, etc.) The bubble can focus also on one sensor to increase its range parameter. This focus could be reached thanks to Signal Processing techniques for example.

2.2.2. The "vehicle" analogy

For the second analogy we take into account is the "vehicle bubble" analogy. This is clearly an extension of the "human bubble" to the car situation in the traffic. Now the virtual sphere is around the car and moves with the car. The car driver should know everything within its bubble, and understand all the information inside the bubble. This bubble information is given thanks to the human driver senses with the help of:

- Signs of other cars and road infrastructure,
- Rules known and respected by everybody,
- Anticipation, prediction, thanks to previous experiences.

Let us continue our analogy with the following example:
The aim of a car driver is to go from one point to a destination without accident with respect to some constraints (time, number of kilometers, price, etc.), thanks to its "bubble" all along the trip.

The aim of a CR equipment is to send its information to the right recipient without accident (good QoS) with respect to some constraints (time, throughput, price, etc.), thanks to its "bubble" as well.

2.3. Information exchange between the "bubbles"

As already explained, the SRB perception will be limited by the sensor capability. The range parameter of a dimension of the SRB can also change according to the environment (obstacles, interferences, etc.) The consequence is that, to better know the environment and to avoid problems as for example the hidden nodes problem in the holes detection sensor, the bubbles should exchange information and therefore communicate. The "Sunny Day" example: "Person A is in a home with no windows. Person B resides in the same city as A, and is in a home that has windows. A telephones B and asks, "Is today a sunny day?" How B does arrive at an answer to this question? B will probably rely on his physical senses to provide data about his surroundings. In this example, vision will be an important physical sense, as B will probably look out a window to evaluate the amount of sunlight outside. B will also utilize his brain to perform the thought-computations necessary to determine an answer. Those thought-computations will be unique to the situation because B is in a particular place, at a particular time, working with a particular set of cognitive capabilities and available information." explained in [16] in the context of human bubble could be simply transpose in our CR context. That means the communication between the bubbles will extend the environment knowing of the CR equipment, and give access to information unavailable at a particular location, at a particular time to the CR equipment (like the hidden nodes example). Because the bubbles are running on SWR technology, they should have all the technological means to establish a radio communication, with the adapted standard to the current situation (distance between them, state of their spectrum maps,...) This communication aspects between the bubbles will be described in details in a further paper.

2.4. The sensors of the SRB

We show that the word sensor it used in its broad sense. It represents all means that can give information of the environment. It could be either
a classical sensor (microphone, etc.) or it could be a smart sensor based on advanced signal processing. We classify the sensors in regards to the layer model we gave in section 1 so that we speak about multilayer sensors. We simply recall here this classification obtained with this model.

Table 1: The sensors according to the simplified three layer model

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Layers</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>User profile: Price, Operator, Personal choices, etc. Sound, Video, Speed, Position, Velocity Security, etc.</td>
<td>Application and IHM:</td>
<td>Sections 3 Example: the Video sensor</td>
</tr>
<tr>
<td>Handover vertical inter/intra networks Standards Load on a link, etc.</td>
<td>Transport, Network</td>
<td>Sections 4 Examples: CPC, LBI BSRS sensors</td>
</tr>
<tr>
<td>Access mode, Power, Modulation, Channel coding, Carrier frequency, Symbol frequency, Handover horizontal, Channel estimation, Antennas beams, Consumption, etc.</td>
<td>Physical, link</td>
<td>Sections 5 Examples: FBS, SMCDS, HSDS, sensors</td>
</tr>
</tbody>
</table>

Table 1 gives a non-exhaustive list of the sensors of each of the three layers. Column 3 shows for each layer which ones will be studied deeper in the following sections of this paper.

3. The sensors of the Application layer

We particularly address in the following the high-level sensors. High-level has to be understood here in the sense that the sensing information come
from the higher layers of the system. From our model, we deduce that it is mandatory to adapt the equipment to the user’s needs, user’s behaviors. In this context we have to detect its presence, to identify him to analyze its behavior and finally to interact with him. The less invasive sensor for that type of purposes is the video sensor. It is now possible to detect, in real time, faces in video sequences. In this section two scenarios using video sensor are described. The first one is the military Mitola’s scenario whereas the second one is more throughput oriented for telecommunications networks. To be able to perform this second scenario, an efficient face characteristics points alignment is needed. A solution based on AAM techniques is described in the same section.

3.1. Mitola’s scenario

In one of his papers, J.Mitola [3] described a scenario which involves a lot of application layer sensors, and particularly the video sensor. This scenario is a military scenario in which after an accident the video sensor should recognize its new holder and act in consequence:

First the CPDA (for Cognitive PDA) should sense the environment: “The military CPDA continuously processes acoustics, video, accelerometer, RF, and other signals from the environment, continuously attributing the signals to ontological objects such as the self, the user, the user’s home (e.g. quarters, bivouac location), the user’s host vehicle (e.g. HMWWV, tank), other known structures and vehicles, and geospatial reference points (e.g. highways, landmarks).”

Then an accident occurs and the CPDA is ejected from the vehicle: “the CPDA recognizes the change in shock and vibration signature between the HMWWV ride (relatively high vibration with occasional shock and intermittent GPS coverage) and the exit from the vehicle (e.g. relatively high acceleration followed by zero-shock/vibration high-speed movement, possibly tumbling, followed by the shock, tumbling of landing). Associated with the shock/vibration profile of the ride, ejection, and landing would be related images, sounds, and RF signatures, such as relatively high RF power from the vehicle’s radio when aboard.”

At the end of the scenario, the CPDA should recognize its new holder and undertake appropriate behavior: “This might include, for example, a call for help via reliable low data rate RF, such as HF. It might then go into a power conservation mode to maximize its probability of resuming its mission once
recovered. If subsequently picked up by hand, the CPDA could compute the facial features and speech parameters of its new holder to determine whether it has been recovered or may be in the possession of coalition or hostile forces. The CPDA might be able to protect its internal data in stages, preserving as much of the data as possible in case it is returned to its rightful owner.”

3.2. Radio link adaptation with video compression changes scenario

This scenario consists basically in using application layer information to take decisions of modification of the radio configuration. The new object-oriented algorithms for video compression are able to generate a variable data stream over the time in terms of data throughput (ratio from one to twenty). A video stream representing a tennis player with the audience in the background for instance, may be divided in two objects: the audience and the tennis court on the one hand for the background of the image, and the tennis player himself on the other hand. This permits to transmit only from time to time the background of the picture, which is very demanding in terms of data throughput otherwise, while the tennis player is frequently refreshed, demanding a low throughput at each time. Consequently, the savings in terms of data to transmit is very significant. Cognitive radio aims at defining and transmitting the optimal radio link for each situation. This requires in particular to take into account permanently the parameters of the algorithms of the video compression in order to reconfigure the radio link. This can go from changes of parameters of the modulation inside a standard, up to a complete waveform reconfiguration. The suggested scenario illustrates the adaptation of the radio link according to the compression of the source in a video-telephony context. A person switches-on his terminal in order to engage an audio-video conversation with another person. At the beginning of the communication, the face of the speaker and the background of the image are transmitted using a traditional compression mode. This requires a relatively high data-rate. Over the time, a model of the person’s face is generated at the transmitter’s side, and sent to the receiver. Once this model is understood by the receiver, the transmitted parameters of the face’s model (orientation, opening of the mouth, of the eyes, direction of the glance) are enough to reproduce the face behaviour at the receiver. This permits to save the data amount required to transmit the face of the speaker, by reducing very significantly the data to be transmitted through the air. This permits to move the video transmission from higher date rate and power consuming radio standards, such as UMTS or WiFi, towards low data rate
standards such as GSM, thus enabling spectrum savings as well as battery savings. The standard vertical handovers are performed thanks to dynamic reconfigurations of the radio link. The use of such video processing facilities in a CR context is detailed in [4]. All the applications which will use video sensor, like face detection and face analysis in the previous scenario need that all the face characteristics points (nose, eyes, mouse, etc.) are well identified and well aligned. This is still today a very big technical challenge, specifically when the user is moving and when the scene illumination is variable. One possible answer for that challenge is the used of Active Appearance Model (AAM). AAM and its improvement are described below.

3.2.1. Active Appearance Model

Active Appearance Model has been proposed by Edwards, Cootes et Taylor [18]. They offer the possibility to jointly syntehize a form and a texture with three Principal Component Analysis PCA. With a data base of objects examples to be modelized we apply an PCA on all the forms and then another PCA on the textures normalized with the average form. We obtain two vectors of form and texture appearance. Then with a third PCA on these vectors we obtain a appearance vector which represents the model. Any modification of this vector permits to obtain new forms and textures of the considered object. When the model receives a new unknow image we put the synthesize model on it and we modify iteratively (using regression matrices or simplex [19]) the appearance vector in order to decrease the error between the model and the unknown object. Thus, after some iterations the AAM model converges and the model is exactly aligned on the unknown object.

3.2.2. Active Appearance Model Improvement

These models are very promising but not yet sufficiently robust against luminosity variations. A promising solution to tackle this difficulty has been proposed in [17]. This work consists in making them more robust in real conditions. It proposes a specific robust pretreatment to lighting variations for deformable models methods. It consists in replacing AAM input textures by oriented maps (Figure 6(f)) extracted from the original textures (Figure 6(a)) specifically equalized on which the orientation of each pixel is evaluated (Figure 6(b)), maped between 0 and Π/2 (Figure 6(c)) and modulated by the gradient (Figure 6(d)) of the image. In addition, an adapted metric to evaluate those new textures during the AAM convergence is used. Authors illustrate their proposal with test on the BioId data base with "nor-
mal illumination and also on a specific database build for luminosity variations performances: the CMU-PIE data base. A face is considered to be aligned with an error $e$ if the distance between the reference and the model normalized by the distance between the two eyes is less than $e$. On the two Figures 7 and 8 the x-scale is the error and in y-scale the percentage of good localization. The proposed method is compared with the classical AAM method [18] and with the CLAHE method after equalization step of the images [20]. An interesting comparison point between the three methods is around 15%. The improvement given by this new method is obvious on the difficult database (see Figure 7). Even when the database is not complicated from the illumination point of view (see Figure 8) the results are interesting. In this situation the proposed method outperforms the classical AAM method of [18]. This work is still under study and other improvements have been proposed, mainly for robustness in position using 3DAAM [21]

4. The sensors of the intermediate layer

From the previous model, we identified several other sensors as load on a link, horizontal handover. We describe below three popular solutions in the literature to obtain information on the spectrum in the vicinity of the considered equipment. Firstly we present the Cognitive Pilot Channel so-
Figure 7: Difficult illumination conditions: base PiE

Figure 8: Normal illumination conditions: base BioID.
olution then another solution based on geo-localization and thirdly the blind standard recognition. The latest is in our point of view the most promising regarding several criteria and this will be illustrated with a comparison. It will be described in detail below. This sensor is very interesting for understanding the X-layer sensor approach. In fact it uses several sensors from the lower layer (physical layer) as bandwidth, access type, modulation type sensors.

4.1. The Cognitive Pilot Channel

The CPC (Cognitive Pilot Channel) is a recent concept issued from the Cognitive Radio (CR) domain. It is mainly studied within the framework of the IST European project E2R. It has been published in [23], [24] and [25]. It has also been proposed to the standardization bodies. The concept is a particular radio channel in which the CR equipment can find information such as frequency band allocation, Radio Access Technologies (RAT), operators etc.

This way to find the RAT thanks to the CPC offers several advantages:

- The connection time to a network could be very short.
- Reduce the computation time
- Consequently reduce the consumption.
- It should facilitate spectrum management like DSA/FSM.

The main drawbacks are:

- Find a common frequency (or frequency band) for all countries and all regions in the ITU sense. For people who know the difficulty of band allocation during WARC\(^1\), this seems a very hard challenge.
- Operators should accept to share information, which today is often hidden for business reasons.

\(^1\)WARC= World Administrative Radio Conference
4.2. Spectrum knowledge thanks to positioning function: the Localization Based Identification method (LBI)

This very simple solution has been published several years ago (using GPS for localization purpose)[26]. The assumption is: ”At each location and at each time there is a predefined set of known standards”. Therefore knowing this information and knowing the location we know the standards available in the vicinity of the CR equipment. Four types of coverage are defined in order to fill the table. Each standard of the previous assumption has a particular type of coverage. This knowledge linked to a loaded database (reconfigurable by downloading) and possibly controlled by the user rights allows the adequate system to be selected.

4.2.1. System description

We briefly here describe the system. More details could be found in reference [26]. The technique proposed would allow the standard to be automatically researched by the terminal without user intervention. A study of the parameters of all the systems currently available allowed to identify the frequency plan in a precise geographic location, as a discriminant parameter. We therefore propose to insert a GPS function into multistandard terminals in order to determine the geographic location. This knowledge eventually also linked to user’s rights allows the selection of an adequate system from a loaded database. This could be re-configured by download.

4.2.2. Types of coverage

Four types of coverage are defined according to their area of use as described in Figure 9.

1. The first is worldwide and does not usually require GPS localisation. It should be stated that there are always exceptions. The following standards are part of this group: UMTS, Globalstar, S-UMTS.
2. Coverage by region (in the ITU sense) or by continent. This type of coverage is relatively easy to manage. The lines follow the time zones. Once again there are exceptions which can complicate handling. With regards to this we have GSM, IS95, PDC and DAB systems etc.
3. Regional or national coverage. Boundary management is necessary. This is the main difficulty in the managing the database. We have systems such as DVB-T, radio FM
4. Local coverage: relatively easy to manage if the center of the transmitter is known and if the landscape isn’t covered by large obstacles (mountains, buildings). DECT, PHS, RLAN, HIPERLAN and other local networks are among this type of system. The frequencies of these stations are assigned by continental region but in practice the user will only have very fragmented rights in limited places. For this coverage manual login is possible. The transmitter location and its coverage span is indicated.

By loading a GPS receiver linked to the frequency allocation table of the geographic location (see Figure 10), the mobile phone constantly knows which systems it can connect to. This table could be stored in the user’s SIM card or in the memory on the terminal. In both cases, it must be re-programmable.

4.2.3. Management of the data base

There are numerous possible solutions on the one hand to manage the database, and on the other hand, check the rights of a user to access such and such network. Two different cases are possible, in the first, the mobile is
free to choose the operator and therefore play on the competition. Though in the second, it is confined to its own provider or those with which it has agreements. Both ideas clash with those of the operator which favours its own network, and the user, who, according to their own cost or performance criteria, would like the widest choice possible. Updating the database can be done in four ways:

- Over The Air Reconfiguration.
- Downloading using the SIM (Subscriber Identification Module) module.
- Downloading through classical network (internet) before traveling.
- Manual reconfiguration in case unidentified. Manual configuration is useful in order to allow modifications in unforeseen circumstances.

These four possibilities are illustrated in Figure 11. This is clearly the most difficult point of this system. The question is: How big should be the database? Coverage management is definitely the crucial point of the system. The optimisation of the management method and the database size are at the root of the problem to be resolved. The system cartography must take the least space possible in the database. This should not be a problem as this is something obtained classically in GPS devices.

4.3. Blind Standard Recognition Sensor (BSRS)

4.3.1. General description

As described in Figure 12, the BSRS sensor analyzes the received signal in three steps. The first step is an iterative process that decreases the signal
bandwidth to be analyzed further, so that the band of analysis is reduced to the only non zero regions. During the second step an analysis is performed thanks to several sensors. Then during the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present. During the second step, different sensors analyze the

bands selected in step one. Many sub-sensors could be used for the recognition of the standard in use as: positioning of the equipment, presence of the telecommunication signal, detection of the carrier frequency, recognition of the bandwidth of the received signal, recognition of the FH/DS signal, recognition of Single/Multi carrier. In our results (see below) only three sub-sensors are used for the recognition of the standards.

4.3.2. Step 1: Bandwidth adaptation

The difficulty here relies in the fact that the ratio between the global bandwidth to be analyzed and the smallest bandwidth parameter to be recognized may be very high. Therefore an iterative adaptation of the bandwidth to be analyzed is performed to solve it. At each iteration, the process analyzes energy in the band with a conventional periodogram, then filters and decimates the samples around the detected peak of energy.

Figure 12: The new standard recognition sensor
4.3.3. Step 2: Analysis with sensors

We chose three sub-sensors to analyse and identify the received signal according with a list of predetermined standards: The bandwidth recognition, Single/Multicarrier detection and FH/DS signal detection. Other sensors could be used to identify other parameters.

4.3.4. Step 3: Fusion

Then during the third step, a fusion of all the information given by the analysis phase is performed in order to decide which standard is present. At the end of the analysis step, three indicators are obtained. The simplest way to make the fusion is to apply some logical rules on these indicators. This method could be improved by the use of a neural network (like a Multilayer Perceptron). Moreover as these indicators give information which could be weighted by a reliability factor, a future work will further explore solutions based on Bayesian network.

4.4. Comparisons of the three described sensors

<table>
<thead>
<tr>
<th>Methods</th>
<th>CPC</th>
<th>LBI</th>
<th>BSRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need of an External service Provider</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Content level (1)</td>
<td>High</td>
<td>Medium</td>
<td>low</td>
</tr>
<tr>
<td>Coverage dependant(2)</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Computational complexity</td>
<td>low</td>
<td>medium</td>
<td>Very high</td>
</tr>
<tr>
<td>Standardization process</td>
<td>Required</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Spectrum consuming</td>
<td>yes</td>
<td>yes</td>
<td>No</td>
</tr>
<tr>
<td>Operator dependent</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Need of an additional link</td>
<td>Yes (CPC itself)</td>
<td>Yes (GPS)</td>
<td>No</td>
</tr>
</tbody>
</table>

Reading table 2, it is very clear that the BSR sensor, except for the computational aspect, fills all the other requirements. Metric (1) of table 2 means that the information given by the method is higher with CPC than With BSRS. In fact CPC will give in addition information about the standard, the operators, the services, whereas BSRS will only give an information of existence of standards (to reach more information imply to demodulate the standard) Metric (2) of table 2 means that the information given by
the method is dependent of the coverage. In fact it is difficult to imagine that CPC gives precise information on WiFi standards in a small specific area whereas BSRS could detect these standards as well as LBI under the assumption the data base is correctly filled.

5. The sensors of the physical layer

The starting point of CR was to optimize the spectrum resources use, considering that most of spectrum is under-used in space and in time. Spectrum sensors are of major importance. In our model, these sensors belong to the physical layer. We propose to describe some of them below.

5.1. Free Band Sensor (FBS)

A radio signal \( y(t) \) received at the antenna is first filtered on a bandwidth \( B_L \) before, then digitized and sent to the detector block that states on the band between: "free" or "occupied". Depending on the reuse type, several definitions exist for a free band. In this paper, we consider that a band \( B_L \) is free if the signal received in this band \( B_L \) is only made of noise (thermal, atmospheric, etc.). In the opposite, e.g. if noise and telecommunication signals are detected, the band is declared occupied. This is a detection issue of signals in noise, which can be stated as the following hypothesis:

\[
H_0 : x(t) = b(t) \\
H_1 : x(t) = \sum_i (s_i(t)) + b(t) \tag{1}
\]

where \( H_0 \) is the free band \( B_L \) and \( H_1 \) corresponds to occupied \( B_L \). \( b(t) \) is noise and \( s_i(t) \) is a telecommunication signal. Depending on the knowledge level of the CR equipment on the telecommunication signals transmitted on
many detection techniques may be considered. Among them we describe below the 3 most known and proposed in the literature: matched filter, energy or power detection, cyclostationarities properties detection.

**Matched filter:**
It is the optimal solution to a signal detection in presence of noise [27] as it maximizes the received signal to noise ratio (SNR). It is a coherent detection method. It necessitates the demodulation of the signal, which means that cognitive radio equipment has the knowledge a priori on the received signal(s), e.g. order and modulation type, pulse shaping filter, data packet format, etc. Most often, telecommunication signals have well-defined characteristics, e.g. presence of a pilot, preamble, synchronization words, etc., that permit the use of these detection techniques. Based on a coherent approach, matched filter has the advantage to only require a reduced set of samples, function of \(O(1/RSB)\), in order to reach a convenient detection probability [28]. In CR context, the main disadvantage for free bands detection is that the equipment should have as many detection chains as the number of potential signals to detect.

**Energy detection:**
Energy detection or radiometer method lies on a stationary and deterministic model of the signal mixed with a stationary white Gaussian noise with a known single-side power spectrum density \(\sigma_0\). A simplified diagram of a radiometer is shown on Figure 14. It can be shown [29] that the statistic test \(V\) follows a **Chi-Two law** (\(X^2\)) at \(2TW\) degrees of freedom. Under \(H_0\) hypothesis this law is centred whereas under \(H_1\) it is not centred with a non centralization parameter \(\lambda\) equal to \(E_s/\sigma_0\), with \(E_s\) the energy of the signal \(s(t)\). For \(TW\) increasing, statistic \(V\) tends to be a Gaussian variable. Figure 15 and Figure 16, show for different values of false alarm probability \((P_{fa})\) the minimum signal to noise ratio \(RSB(E_s/\sigma_0)\) required for the detection in function of \(TW\). This theoretical result shows that radiometer can detect a weak signal within noise. Nevertheless, it supposes a precise knowledge of the noise level \(\sigma_0\). In the contrary, as for instance \((1-\epsilon_1)\sigma_0 \leq \sigma_0 \leq (1+\epsilon_2)\sigma_0\),

\[
B_L, \quad \frac{\int_{-T}^{T} r(t) x(t) \, dt}{\sigma_0} \quad \xrightarrow{\text{tends to be a Gaussian variable}} \quad \chi_\lambda^2
\]

\[
\begin{align*}
\text{Figure 14: radio meter diagram}
\end{align*}
\]
radiometer performances decrease [30] even if $TW$ is infinitely increased, as it is shown on the theoretical curve of Figure 15. $U$ is defined by:

$$U = 10 \log_{10} \left[ \frac{1 + \varepsilon_2}{1 - \varepsilon_1} \right]$$  \hspace{1cm} (2)

[31] and [32] give examples of statistical distribution of $V$ when the searched signal is an amplitude modulation one or has been submitted to a Rayleigh, Rice or multi-path channel. In current telecommunication systems, channel estimators permit to evaluate the channel properties and noise level thanks to the knowledge of a sub-part of the transmitted frame. But these estimators require knowing on the signal itself which is, obviously, impossible in CR systems context. Therefore, we need testing techniques independent of the noise level knowledge.

**Cyclostationarities properties detection:**
As the searched signal is a telecommunication signal, an interesting alternative consists in choosing a cyclostationary [33] model instead of a stationary model of the signal. This model is all the more so interesting that noise is stationary-like. Detection problem (1) becomes a test on the presence of the cyclostationary characteristic of the tested signal. If $x(t)$ is a random process of null mean. $x(t)$ is cyclostationary at order $n_0$ if and only if his statistic properties at order $n_0$ are a periodic function of time. In particular, for $n_0 = 2$, processus is cyclostationary in the large sense and respects:

$$c_{xx}(t, \tau) = E(x(t)x(t + \tau)) = c_{xx}(t + T, \tau)$$  \hspace{1cm} (3)
parameter $T$ represents a cyclic period. If processus $x(t)$ is stationary then its statistic proprieties are independent of time. In the context of a cyclostationary modeling, covariance function can be developed in Fourier series with variable $t$:

$$c_{xx}(t, \tau) = c_{xx}(\tau) + \sum_{\alpha \in \psi} C_{xx}(\alpha, \tau) \exp^{i2\pi \alpha t} \tag{4}$$

with

$$C_{xx}(\alpha, \tau) = \lim_{Z \to \infty} \frac{1}{Z} \int_{-Z/2}^{Z/2} c_{xx}(t, \tau) \exp^{-i2\pi \alpha t} dt \tag{5}$$

Sum 4 is made of harmonics of the fundamental frequencies, determined by the periods of $c_{xx}(t, \tau)$. These fundamentals frequencies either represent carrier frequencies, or data rate frequencies, or guard intervals of the signal, etc. Parameter $\alpha$ is called cyclic frequency, $\psi$ is the set of cyclic frequencies and $C_{xx}(\alpha, \tau)$ is called the covariance cyclic function. In the context of a stationary processus, $\psi$ is restricted to null set. The choice of a cyclostationary model for the signal leads to consider a free frequency band as a hypothesis test on the radio signal $x(t)$:

if $H_0$ $x(t)$ is stationary and considered band is free,

if $H_1$ $x(t)$ is cyclostationary and considered band is occupied.
This leads to a cyclostationarity test instead of a noisy signal detection. This leads the solution independent of noise. Several articles [33], [34], [35] and especially [36] propose different tests on a cyclic given frequency. In [37] a test is proposed and permits to test a set of cyclic frequencies (for unfiltered signals) enabling to improve detection performance. A convincing result from [37] is given in Figure 17.

The vector of parameters of this sensor will comprise one parameter which say yes or no if the band is or not free. A second parameter could be the reliability of the decision $H_0$ or $H_1$. This second parameter could be used by the decision making engine to improve the decisions at a higher level of the equipment.

5.2. The Bandwidth Recognition Sensor (BRS)

In [12] it was claimed that, in the frequency domain, the channel bandwidth (BWc) was a fully discriminant parameter. To find the bandwidth shape on the received signal a choice has been made to perform a power spectrum density (PSD) on this signal in order to obtain its BWc shape. This shape is compared with reference spectrum shapes given by equation 6.

\[ \hat{\gamma}(k) = \sum_{p=1}^{P} |F_{\text{em}}(l \frac{f_p}{f_e} - k)|^2 \gamma_{\text{mods}}(\frac{f_p}{f_e} - k) \]  

(6)

Figure 18: The RBF neural network
With $F_{em_s}$ the filtering shape (Nyquist Square Root, for example) of the modulated carrier $P$ of the considered standard $S$ and $\gamma_{mods}$ the Power Spectrum Density (PSD) of the modulation of the carrier $P$ of the standard. This comparison is performed using Radial Basis Functional Neural Networks (RBF NN). Using the RBF NN, the received signal PSD is compared with the reference signals PSD. Then a neuron will be active. To each neuron number $i$ corresponds the bandwidth of the standard number $i$.

5.3. Single/Multi Carrier Detection Sensor (SMCDS)

The overall results presented in [12] show that the recognition rate between DVB-T and LMDS on the one hand, DAB and DECT on the other hand, is not good enough. Therefore we propose to improve this recognition adding a new sensor that discriminates between single and multi-carriers systems based on Guard Interval (GI) detection. It is well known that a GI is inserted in multi-carriers systems in order to avoid inter-symbol interference (ISI). There are several possibilities for creating this GI. The simplest and the most usual way is to copy the end of the symbol in the GI. After the computation of the autocorrelation function, the cyclic frequency corresponding to the GI is derived. An example of this detection is presented in Figure 19.

![Figure 19: Detection of GI in OFDM signal (Symbol OFDM 2K, GI/Tu = 1/6)](image.png)
5.4. FH/DS Signal Detection Sensor (FDSDS)

The results previously presented with the fusion of the two previous sensors are not sufficient yet. It fails in the discrimination of Bluetooth and IEEE 802.11b at 2.4 GHz in FHSS mode. In this situation, the two standards co-exist at the same time in the same frequency band, so the resulting spectrum is the product of the original spectrum and consequently the previous sensor does not run correctly. Therefore, we need to find another parameter. For that purpose we decide to find the spread spectrum type which is in this situation a discriminating parameter. A previous study has been proposed in [22], [39], a more efficient solution has been proposed in [38]. This solution uses a Choi-William’s transform (see Figure 20 followed by a segmentation of the obtained image. Then, thanks to a appropriate criteria, which consider the length, the starting and the duration of each segment, the obtained results are very promising.

6. Conclusion

This paper introduces the new concept of the Sensorial Radio Bubble for Cognitive Radio equipments, typically smart terminals. As the human sensorial bubble gives information to a person of its surrounding environment thanks to the five human senses, the SRB provides to the cognitive
radio equipment knowledge about the equipment environment. The SRB is composed of sensors of all layers of the OSI model. We simplified the OSI decomposition in 3 layers and gave an example of sensor for each of the 3 proposed layers: physical, intermediate and application layers. The SRB is a multilayer view of the sensing for cognitive radio, beyond the usual view which is often limited to spectrum issues. The SRB is the ”observe” subpart of the cognitive cycle and provides the cognitive engine of a cognitive radio equipment with all the necessary information to take reconfiguration decisions of the radio chain so that the equipment better runs. Moreover, by analogy to the human sensorial bubble, we also believe this will permit the cognitive radio equipment to plan his behavior in order to predict and anticipate its reaction to environment evolution. This is the scope of some of our next working items in the field of decision taking for cognitive radio. In that sense, based on our previous work on reconfiguration management, this will permit to have a global view of the cognitive cycle: sense, decide, adapt.

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