ORIENTED PROCESSING OF COMMUNICATION SIGNALS FOR SENSING AND DISSEMINATED SPECTRUM MONITORING

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ABSTRACT

This paper aims at providing elements on the implementation of oriented processing facilities in order to improve either disseminated sensing or disseminated Spectrum Monitoring (SM) within Software Defined Radios (SDR) and Cognitive Radios (CR).
The needs and constraints relevant to civilian sensing and SM applications are briefly introduced. Then, the main approaches for answering these needs are exposed and discussed. Considerations about suitable signal processing algorithms, embedded radio components and embedded computing devices are deepened. Illustrated examples are given from simulations and from real field recordings. Procedures relevant to disseminated sensing and SM are pointed out and possible network implantations are suggested. We conclude about strong opportunities provided by oriented processing and the advantage of including these techniques and procedures within standards.
The concepts and the research leading to these results are partially derived from the EU 7th Framework Programs (FP7) ICT-E^{2}R and ICT-QoSMOS ([5], [12]).

1. INTRODUCTION

In the SDR and CR area, sensing is seen as a key function in order:

- to choose carrier frequencies for transmission, and more generally to enhance the spectrum usage efficiency by finding spectrum access opportunities (in various dimensions as time, frequency and space) without interfering with the other users of the band and adjacent bands.
- To manage flexibility in spectrum allocations, priorities among several communication services even with infrastructures and terminals that share the same frequency bands.

Numerous previous and current works are relevant to sensing procedures, to implantation with future terminals and networks ([5], [6], [7], [8], [12]), and to standardization ([9], [10], [11]).

In the SM area, checking the spectrum usage and measuring communication signals are basic functions in order to verify the convenient use of frequency allocations, and the quality of communication signals and services. Thus, the combination of geo-location and sensing capabilities within wireless terminals is seen as an opportunity for future SM applications by regulators and telecommunication administrations.

2. OBJECTIVES OF SENSING AND SPECTRUM MONITORING

2.1. Sensing within Cognitive Radios

Sensing within CR radios aims at providing elements to the cognitive manager in order to enhance radio access efficiency, to facilitate interference mitigation, to manage service priorities, etc. ([5],[6],[12]). The purpose of sensing is thus mainly "communication oriented".

Within CR, sensing may be implanted

- by cooperative techniques taking into account dedicated "beacon" signals such as DL/UL-CPC (Down Link and Up Link Cognitive Pilot Channel). These techniques usually mix broadcasting of information towards terminals (DL-CPC) and infrastructures (UL-CPC) thanks to dedicated messages, and channel sounding techniques; Spectrum and signal measurements are based on the use of a CPC signal that is easily recognized in the radio environment thanks to its a priori knowledge.
- by "autonomous" procedures performed by terminals, that deal with the local radio-environment (search of available spectrum bands, etc.). In this approach, signal

recognition capabilities are necessary for the CRs' sensing to achieve measurements on either useful or interfering signals and to provide reliable information to the cognitive manager.

2.2. Spectrum Monitoring

Objectives, requirements and means for SM are quite different from the sensing ones. Indeed, they are more "regulator oriented".

Traditional ITU Spectrum Monitoring Objectives, Requirements and Recommendations are described in [1]. SM usually deals with a very large set of signals over very wide frequency ranges, in order

- to perform accurate bandwidth and power level measurement,
- to detect abnormal spectrum usages:
    - o abnormal spectrum or power characteristics of regular signals
    - o unexpected signal in the allocated frequencies, even if not interfering
- to identify the nature of abnormal signals
- to locate abnormal transmitters

Figure 1 illustrates the large variety of signals to be taken into account by SM sensors and systems in Ultra High Frequency (300 MHz - 3 GHz)

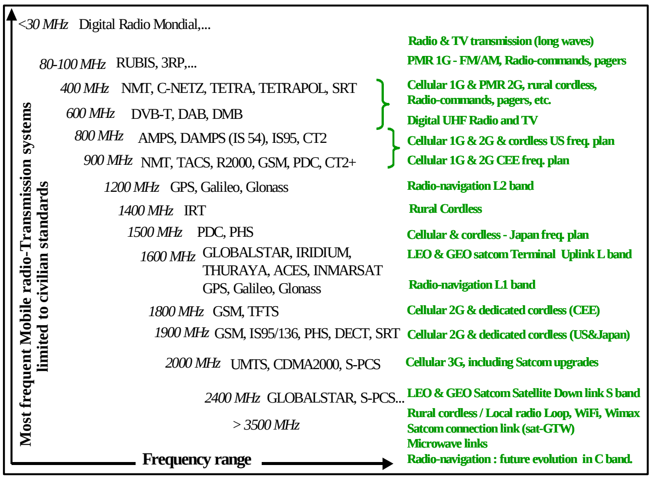


Figure 1: Civilian communication signals to be processed by SM

Thus, performing SM nowadays requires numerous and cost effective specialized materials and labour. In addition, urban zones and modern wireless radio access protocols largely increase the complexity, the diversity and the specialization of the signal processing and of the SM operators.

3. MERGING SENSING AND DISSEMINATED SPECTRUM MONITORING

As mentioned above, both sensing and SM applications have to deal with highly diverse and complex radio environments, in order to produce reliable measurements and diagnosis of radio environment. This requires some recognition capabilities of radio-signals. Moreover, the characteristics sensed from radio interface have to be sent to upper layers (cognitive manager, network manager, SM center, etc.) for both applications.
Thus, operational means of sensing and SM may be separated, but technical means and radio interface processing procedures are quite similar.

In practice, when facing complex radio-environments, highly diverse signals and radio access protocols, harsh propagation conditions (indoor, dense urban), the dissemination of numerous geo-located radio frequency sensors would offer numerous advantages in order to enhance dedicated fixed and mobile SM systems :

- a global geographical coverage of the spectrum would be provided, especially in urban zones and indoor configurations,
- future sensing and Radio Frequency (RF) devices of cognitive terminal will cover very wide frequency ranges (numerous frequency allocations useable by the same device).
- sensing provides a reliable indication of local spectrum quality, and a reliable alert of spectrum degradation at any location and at any part of the wide frequency ranges that are covered.

Following this idea, several projects such as URC ([7], [8]) proposed technical approaches and operational procedures relevant to disseminated SM.

- by using dedicated miniaturized SM devices on urban infrastructures (traffic lights, etc.)
- by using geo-location + sensing capabilities of future mobile radios.

This later trend especially is now supported by several action at ITU-R ([2], [3]). The main ideas relevant to disseminated SM merged with CRs' sensing are the following:

(I) to take the direct benefit of CRs' sensing for SM by sending results from CR to SM centers (in addition to cognitive manager and to network manager). Sensing data collected at a large scale would give maps of "hot spots", of abnormal radio environments, of coverage lacks, etc., in order to prepare SM dedicated missions.

(II) To perform in-situ signal analysis that would be dedicated to SM applications, before sending signal samples + results to the SM centers such as in (III). Here, the pre-analyses would be performed by the terminal itself in an off-line upgraded sensing procedure. Specialized materials and operators would be required for higher level analyses only.

(III) To collect signal samples on the field and to send them to the SM centers with secured transmission procedures (off line dedicated message services during idle states). This would allow off-line and distant pre-analyses by specialized materiel and operators before in-situ verifications

In most of these cases, recognition of signals and even identification of signal transmitters appear as an added need.

4. STAND ALONE AND ORIENTED PROCESSING OF COMMUNICATION SIGNALS

4.1. Brief overview

For both sensing and disseminated SM, the preceding discussion points out a crucial need for reliable radio measurements of communication signals and for diagnosis of receiving conditions, with a reasonable complexity (that should remain compatible with low size/power computers that are embedded into terminals).

To answer this need, three main approaches for signal processing within CR terminals may be defined:

- **Stand-alone processing** operates on radio terminal with neither a priori information nor databases. This technique appears to be a back-up capability to process analog signals and unexpected digital signals in the most flexible way (database not available or not precise enough, unexpected transmitters that are present in the neighborhood, jamming sources, etc.). In practice, a set of elementary stand-alone techniques are based on time signal and on spectrum measurements. But the practical reliability of these basic techniques is poor. Enhanced computations such as spectrum correlation, neural network recognition, etc., may upgrade the performance, but these approaches necessitate more computations that are not compatible with low power / low size embedded computing devices before years.

- **Oriented processing** operates with the help of databases and a priori information (frequency allocations, signal nature in allocated frequency bands, modulation characteristics, etc.), in order to lead analyses with an "expert guidance".

A special class of oriented processing is the set of data-aided techniques: parts of a priori known reference signals (such as CPC signals, middambles, pilot codes, etc.) are directly used for detection and identification of communication signals. Data-aided techniques are well suited to face most of the civilian communication signals and they will be deepened in the following part.

- Finally **cooperative networked sensing** involves sets of terminals within a geographic area, ensuring improved identification and location capabilities of transmitters thanks to exchanges of collected data among terminals and network infrastructure. This applies mainly to data fusion of sensing information (including message exchange protocols) rather than to signal processing at the radio link (see § 6.1).

4.2. Oriented processing with signal model data bases

Oriented processing uses a priori information about the processed signal such as frequency allocations, modulation characteristics, coding scheme characteristics, that are usually included in signal/network model data bases (semantic description of signals). The general philosophy of the processing is illustrated in figure 2:

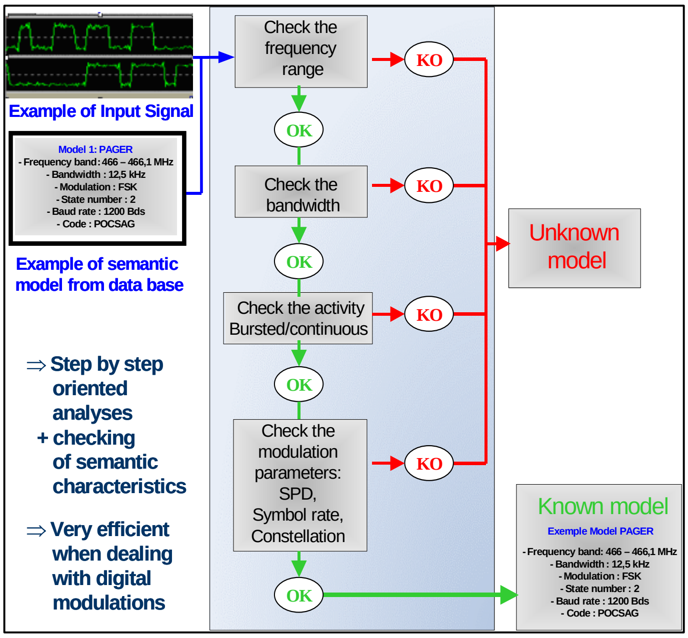
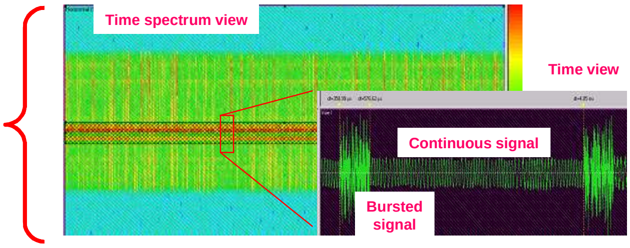


Figure 2: Philosophy of oriented processing

This is practically implanted by performing a set of coupled statistical estimators on the measured signal, and by testing a progressive "arborescence of hypothesis". Step by step oriented analyses and step by step checking of semantic characteristics lead to parallel measurement and recognition of signals. Each step confirms and enhances the previous ones, and prepares the next one. Figure 3 gives practical examples of oriented analyses applied to digital signals such as radio-cellular, microwave links, etc.

A/ Wave Form Structure characterization

Narrow band / wide band signal
Continuous / bursted signal
Frame and synchronization characteristics
Radio Access protocol characteristics
(FDMA,TDMA,CDMA, ...)



B/ Estimation of modulation parameters

Signal bandwith, Carrier frequency
Modulation rate, Number of states, Constellation
Shift (FSK and CPM), FM depth, AM index, etc..

Signal demodulation

(AM/FM,CPM, PSK, QAM, FSK, OFDM, etc)

Analyses of coding scheme

Signal identification

Data base, semantic descriptions, etc.

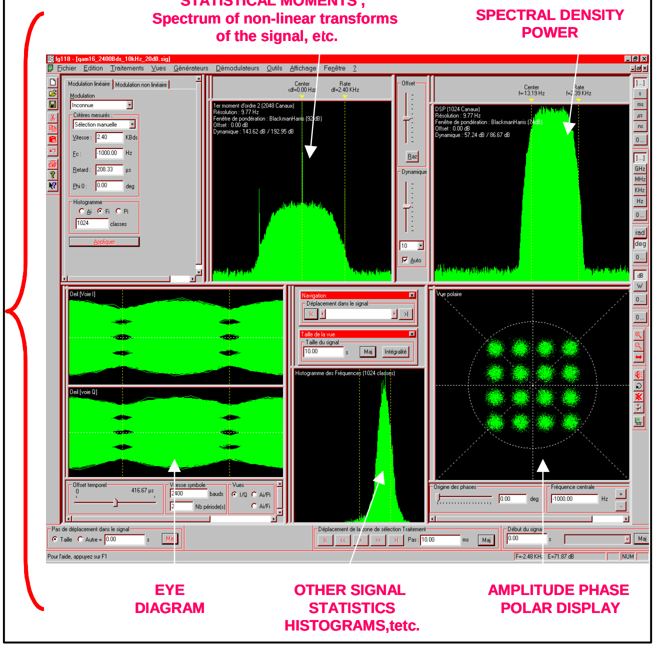


Figure 3: Examples of oriented processing for digital signals

Figures 4 and 5 give examples of statistical tests that are applied to radio-communication signals in order to provide reliable estimators of their modulation characteristics. More details can be found in [1], [3] and [5].

Technical purpose	Power measurement	Estimation of center frequency	Estimation of Symbol rate		Synchronization of symbol + demodulation	
Statistical estimator / Signal example	Spectrum Power Density	Spectrum 1st moment order 2 E[|x|²]	Spectrum 2nd moment order 2 E[x²]	Spectrum 2nd moment order 4 E[x⁴]	Eye Diagram & Histograms I/Q, Amplitude phase frequency.	Eye Diagram & Polar Diagram
FSK2 Ind. 1 SNR 20 dB "PMR like"						
GMSK Ind. 0,5 SNR 20 dB "GSM like"						
O-QPSK Roll off 0,25 SNR 20 dB "CDMA 2000 UL like"						
QPSK Roll off 0,25 SNR 20 dB "UMTS like"						

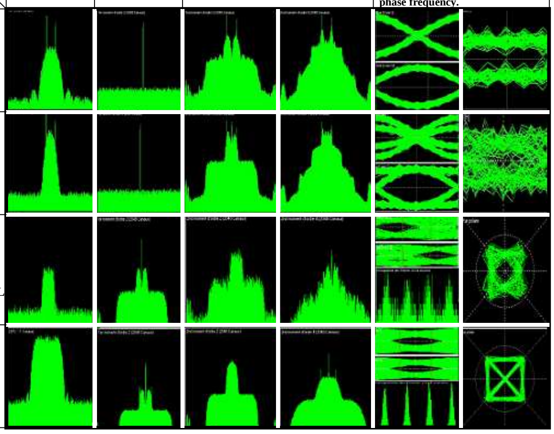


Figure 4 : Examples of statistical tests applied to processing of digital single-carrier signals (PMR, GSM, UMTS, etc.)

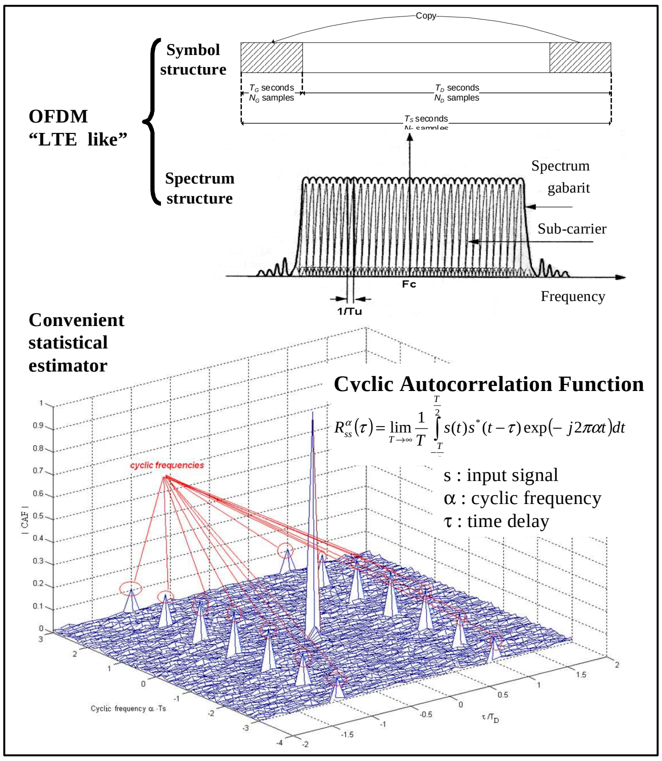


Figure 5 : Examples of statistical tests applied to processing of digital multiple-carrier signals (DVB-T/H, LTE, etc.)

4.3. Special case of data-aided processing

Data-aided processing is a very efficient approach for both signal measurement and identification in the same process. It is based on matched filtering (through inter-correlation computations) and on detection tests of reference signals that are present within the waveform. It is most convenient when dealing with digital civilian standardized waveforms that include low combinatory known sequences such as synchronization words, middambles, pilot codes, etc. in order to achieve efficient synchronization and propagation equalization.

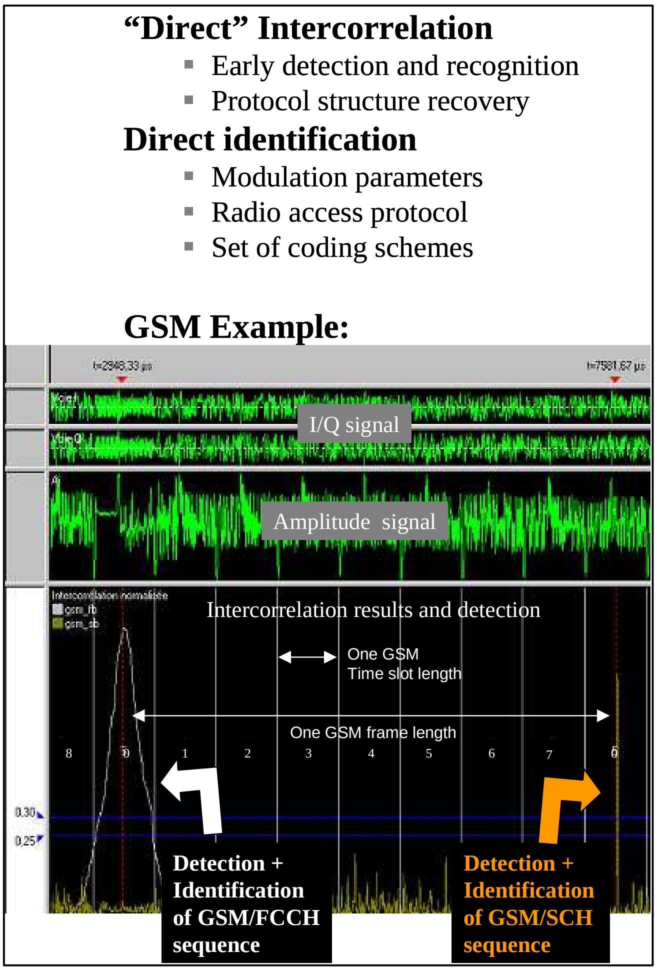


Figure 6 : Examples of data aided processing of radio-communication signals (GSM, UMTS, DVB-T & LTE)

5. ADVANTAGES AND DRAWBACKS

Cooperative and data aided techniques are much more suitable than stand-alone techniques because measurement and recognition processes directly target the modeled signal, thus both processes performed in parallel enhance each other and the combinatory of the analyses is much restricted.

The practical consequences are the following:

- shorter integration within statistical estimators
- more reliable and more accurate parameter estimations
- reduced global computing

Among oriented processing, data-aided techniques apply very efficiently when a low combinatory hypothesis of reference signals has to be taken into account. Thus,

- data aided techniques are usually well suited for modern digital civilian radio-communication standards, such as digital PMR, GSM/GPRS/EDGE, 3GPP/UMTS DL, 3GPP2/DL, DVB-T/H, 802.11x, 802.16x, LTE, etc.
- by respecting the same order of ranges for complexity and time response, data aided techniques are usually more sensitive and more accurate than all other techniques,
- medium interference cases are often diagnosed with these techniques.

Finally one may recommend the prior use of oriented processing. Shortcuts in the analysis with data-aided techniques, should be used as soon as hypothesis are available about the nature of the measured signal (that will confirm identity, accelerate and strengthen measurements).
As they usually require high computing, off line stand alone techniques should be used only when other techniques fail or when model data bases are incomplete (for example at the SM centers after transmission of their signal recordings by CRs).

6. PRACTICAL IMPLEMENTATION WITHIN COGNITIVE RADIOS FOR SENSING AND SPECTRUM MONITORING PURPOSES

6.1. Considerations relevant to the protocols

As suggested by the main current standardization trends ([2], [3], [9], [10], [11]), oriented processing within cognitive terminals should be supported by dedicated protocols and dedicated message services such as CPC, radio enablers, etc., for both sensing and SM applications. Following the approach of [12] and focusing on radio interface measurement for both sensing and spectrum monitoring, a mesh network topology is suggested in figure 7 and a complete procedure is proposed in figure 8.
This procedure may include

- network to terminal transmission of information relevant to frequency usage, to primary users and secondary users (white space location), by "Public Advertiser" Cognitive Pilot Channels and/or other radio enabler techniques,
- Local check/upgrade of the signal model data bases within the terminals.
- Terminals' sensing/monitoring on the RF link:

- o measurement and recognition of signals and networks that are received at the local environment.
- o recordings of signal samples for further transmission and deeper analyses by specialized operators.

- Terminals' to network (including cognitive manager) report of sensing data through dedicated message services
- Terminals' to SM center report of sensing data, with additional off-line delayed transmission of recorded signal samples through secured message services.

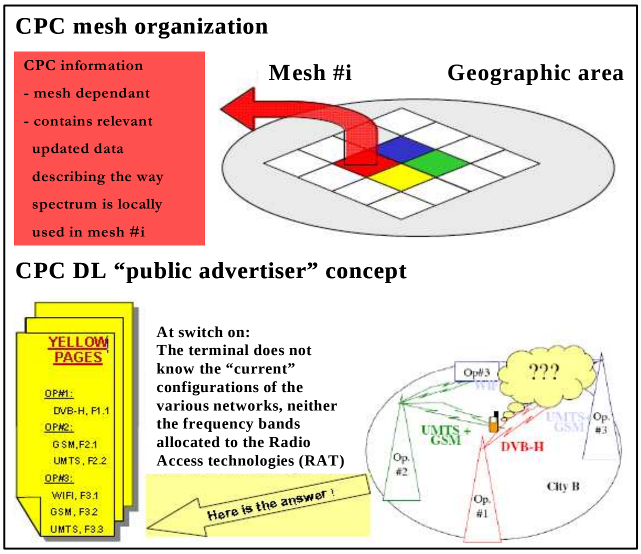


Figure 7: Mesh topology for a CPC "public advertiser" ([12]).

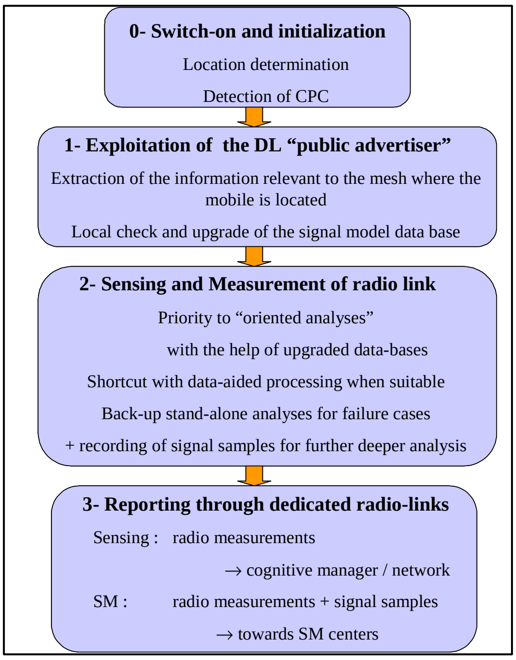


Figure 8 : Example of sensing + measurement protocol for a cognitive terminal (extended from [12]).

An illustration of this procedure and of the relevant links is given in figure 9.

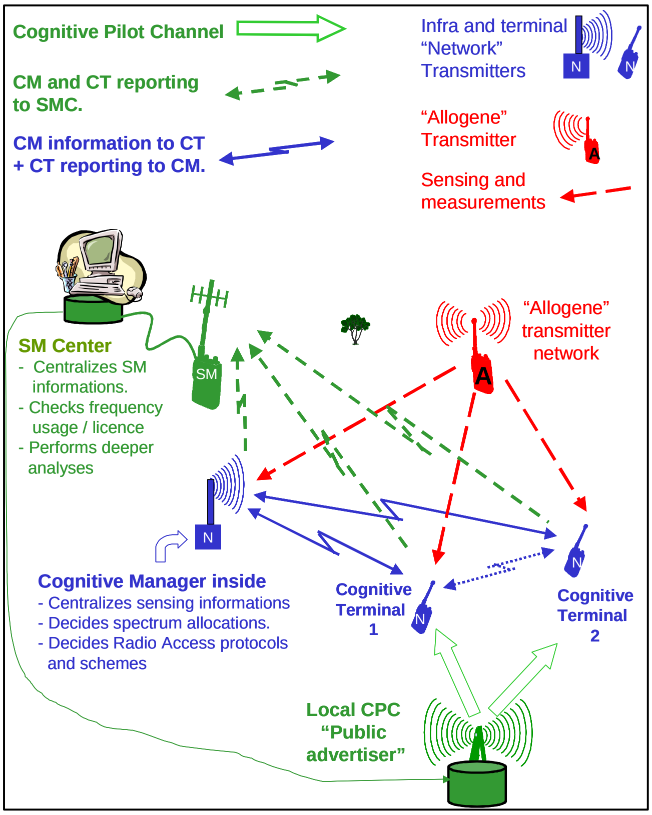


Figure 9: Illustration of a possible network structure for sensing + spectrum monitoring by using cognitive radios.

6.2. Considerations relevant to embedded Hardware and Software

Practical implementation of oriented processing of communication signals requires standard radio performance and signal analyses over convenient signal durations, and convenient bandwidths.

For sensing and SM within restricted areas, and considering the main terrestrial civilian radio-communication standards that are involved in the definition of future software cognitive and opportunistic radios, the following typical values would match most of the requirements for operational applications

- Radio performance similar to standard requirements
- Sensing and SM analyses performed over snapshot of 50-100 ms signal duration over 10-40 MHz bandwidth
- Light real time constraints for sensing recurrence period from 1 to 10 seconds
- Recording/storage capabilities of CRs: a few GBytes.

- Delayed transmission capabilities of signal recordings to the SM centers for further dedicated analyses (dedicated secured message services during “idle states” of cognitive terminals)

Thus hardware requirements for sensing are similar to requirements of future terminals. In addition, software requirements appear to be compatible with expected future embedded computer performance.

7. CONCLUSION

This paper presented several technical arguments showing the strong interest of oriented processing within cognitive radios in order to perform either sensing or disseminated spectrum monitoring:

- Analyses performance of RF signals are largely upgraded,
- Signals are identified and measured in the same process
- Computations are often reduced.

The relevant network procedures meet the current standardizations trends, and no additional radio frequency performances are required for cognitive terminals. Finally, complexity of the procedure should be compatible with future embedded computing devices.

Thus oriented processing of radio-communication signals appears as a major technical opportunity for future cognitive radios and for related radio access concepts that could take place in the current and future standardization efforts relevant to 4G radio networks.

8. REFERENCES

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