A SIGNAL IDENTIFICATION APPLICATION FOR COGNITIVE RADIO

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ABSTRACT

One of the most important aspects of cognitive radio (CR) is that it proposes methodologies to increase current spectrum efficiency. One way that should be followed for this purpose is let the secondary users use the unused parts of the spectrum for a given geographical space, at a certain time. This requires a certain level of knowledge on the characteristics of the communications in the geographical area of interest. If the signal types and communication technologies existing in the area are identified, then it will be possible to determine how to let the secondary users communicate through the medium in a safe, reliable way with high QoS (Quality of Service) and, without interfering and harming the primary users' communication. Secondly, if the signal type of the primary user is known, alternative methodologies can be applied to allocate the secondary user. For instance, if the primary user's signal has the frequency hopping property, allocation of secondary user can be done accordingly. Finally, communication regulation commissions have regulations on some of the frequency bands indicating the type of the signal for that band. Intruding signals, which are not expected in the frequency band, can also be identified using signal identification techniques.

1. INTRODUCTION

Through the evolution of first generation wireless systems to third generation wireless systems and beyond, two parameters a) consistently increasing number of users, b) wider bandwidth requirement of data and multimedia transmitting technologies constantly reduces the availability of frequency spectrum. Besides, the variety of civil and military based wireless communications applications indicates a scarce of frequency band allocation when the FCC frequency allocation chart is taken into consideration [1][2]. However, the occupational difference between static emitters like TV and radio wave transmitters and dynamic emitters like cellular communication systems are not distinguishable on the FCC frequency allocation chart. When the real spectrum measurements are taken into consideration the crowdedness depicted in FCC chart becomes an unreality and measurements indicate that there is an inefficient spectrum usage [3], [4] from the aspect of dynamic users.

Adoption of newly technologies attracted the focus of governmental regulators and research institutions on the issue and FCC's Spectrum Policy Task Force's report published in 2002 [5] is a milestone which the underutilization of the spectrum is investigated. This report recommended support of new technologies for better utilization of the frequency spectrum. In 2003, FCC issued "Notice of Proposed Rule Making" employing *cognitive radio technologies* for flexible, efficient and reliable spectrum use [6].

There were numerous individual studies for computationally intelligent and flexible wireless communication systems prior to year 2000 [7][8], however a complete and precise approach under the name of cognitive radio is constituted by Joseph Mitola III with his PhD dissertation called: "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio" as:

"The term cognitive radio identifies the point in which wireless personal digital assistants (PDA) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to:
(a) Detect user communications needs as a function of use context, and
(b) To provide radio resources and wireless services most appropriate to those needs."

Cognitive Radio had been perceived as an extension to the concept of Software Defined Radios (SDR) in the first place, later the cognitive radio concept is suggested also to include enhance extensions on spectrum awareness and communication environment adaptation [6]:

"A cognitive radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which is operates. The majority of cognitive radios will probably be software defined radios (SDR), but neither having software nor being field programmable is requirements of a cognitive radio."

An extended study on the aspect of physical layer requirements of cognitive radio [9] indicated three key features for cognitive radio systems: a) a cognitive radio must be able to identify the unused spectrum segments (Spectrum Sensing) b) a cognitive radio must be able to change signal frequency and spectrum shape to fit into the unused spectrum segments (Flexibility) c) a cognitive radio must not cause harmful interference to the primary users (Interference Avoidance).

[6] indicates the use of spectrum by secondary users without effecting the communication of licensed (primary) users to increase the spectrum efficiency. [3] offers cognitive radio – with its spectrum sensing capability – as a secondary user platform. Several methodologies proposed previously [10] [11] for signal detection under spectrum sensing concept, however the concerns of these methodologies are to detect a signal in a given frequency spectrum but not to identify the signal or the communication technology. However detection and identification of the primary users occupying the spectrum has important benefits compared to only detection. This paper indicates these benefits and proposes a simple signal detection methodology with its application.

Through this paper, in Section II, firstly more detail about current usage of the spectrum, spectrum sensing techniques, spectrum monitoring and their limitations will be given. In Section III, requirement for signal identification and the proposed approach relating spectrum sensing and signal identification will be explained. An application of the proposed methodology will be given in Section IV. Finally, the conclusions will constitute Section V.

2. SPECTRUM SENSING & MONITORING

The main difference between static and dynamic occupation of the frequency spectrum stems from the intermittent usage by dynamic users resulting with the white spaces in frequency, time and space. This paradigm is one of the main causes that contribute to the inefficient usage of frequency spectrum. On the other hand, when the whole spectrum is taken into consideration, it can be realized that the intensive use of spectrum is valid for frequencies lower than 3 GHz [11]. One way to come up with a solution to these problems can be the new spectrum allocation auctions. This may temporarily be a solution however; the same problems will show themselves as the time passes by. Besides that, new auctions require new equipments both at the provider and user side which brings complexity to the current wireless communication systems. Therefore, a new approach for eliminating the underutilization of the frequency spectrum is necessary. This approach can be applied through cognitive radio technology by inserting the secondary users to the current wireless networks. The occupation of secondary users should be conducted in a reliable and flexible way so that the communication of primary users will not be effected or there will be no loss at the quality of the service that they get. So the spectrum sensing should be executed in an appropriate and accurate way that there should be no boundary or limitation on communication of primary users.

As indicated before, spectrum sensing is implemented via digital signal processing techniques of signal detection. In general there are three ways of implementing spectrum sensing in physical layer: match filtering, energy detection and cyclostationary feature detection. All these three techniques have advantages and disadvantages against each other. For instance the match filter has the maximum level of signal to noise ratio (SNR) however this technique requires demodulation of the received signal and needs dedicated receivers for each signal type. Energy detection has a simpler approach but it has a lower limit of $O(1/SNR^2)$ for samples and there is a probability of miss detection or wrong detection because of the threshold estimated [12]. Finally, cyclostationary feature detection is the most complex but accurate one that requires specific information about each signal type or technology.

Spectrum monitoring methodologies bring a statistical approach to the problem of efficient spectrum usage. It was previously indicated that the information depending on the regulations and licenses may be deceptive when compared with measurements conducted. The utilization of spectrum is related to the dynamic usage which is dependant on the parameters like transmitter power, antenna types, location information of the transmitters and local environment effects. Therefore, spectrum monitoring methodologies provides statistical models of the utilization of the frequency spectrum as a function of time, space, frequency and angle. Monitoring activities are conducted by either by classical measurement methodologies including the equipments of spectrum analyzers, antennas, data recorders and computers [13] or by using data collection equipments like wireless snuffers [14]. The spectrum monitoring methodologies aim to:

- Collect data to build a statistical model for the frequency band usage
- Investigate the usage variation of signals in different environments, times etc.
- Investigate the possibilities of congestion of signals
- Collect the information necessary for effective regulations of new bands like 5 GHz band

Cognitive radios sense the spectrum using the signal detection methodologies introduced in this section. Besides that, they can also benefit from the statistical information that is provided by spectrum measurement activities. However, if the wireless signals of primary users are identified following the detection procedure, secondary user allocation procedures of cognitive radios will benefit from this information.

3. SIGNAL IDENTIFICATION

Every wireless communication technology emerges through a series of steps. Mostly starts with the definition of the requirements for the technology, as a project, by a consortium or a group that is constituted by fore coming people, institutions, and companies who have expertise and/or knowledge on the related systems to the proposed technology (for instance, Wideband Code-Division Multiple-Access [W-CDMA] is based on the access technique proposed by ETSI Alpha working group in 1999). Because the channel to the transfer and receive wireless communication signals is our physical environment, characteristics of the signal traveling in the medium is strictly defined through the development of the project. Generally, the process ends up with the commercialization of the technology, which also brings the solid definitions about the technical aspects such as frequency band requirements, data rates, frame lengths, modulation techniques, coding technologies, multiplexing schemes etc.

The solid definition of the technology, related to the transmitting signal, enables us to infer distinct features of the technology's transmitted signal. Spectrum sensing concept proposes several signal detection methodologies however, besides the detection of wireless signals; identification of the wireless signals depending on the definitions of the wireless technologies and regulations provides some other information like multiple accessing methods, carrier information, signal bandwidth, center frequency, power level, etc., with some statistical information about the monitored frequency spectrum. These new parameters enhance the spectrum sensing capabilities of cognitive radios form the aspects of:

- Depending on the identified signal, allocation of the secondary users can be done to reduce interference with the primary users. For instance, allocation of the secondary user in the spectrum can be estimated by taking the knowledge of the bandwidth and the center frequency of the primary user into consideration.
- If the signal type of the primary user is known, alternative methodologies can be applied to allocate the secondary user. For example, if the primary user's signal has the frequency hopping property, allocation of secondary user can be done accordingly and if the primary user has some unused slots secondary user may adapt its communication using this information.
- ITU has regulations on some of the frequency bands indicating the type of the signal for that band. Intruding signals, which are not expected in the monitored frequency band, can also be detected using signal identification techniques.

3.1 Proposed Methodology

The proposed methodology invokes a tree based identification algorithm which uses a methodology for signal identification based on some previously determined criteria. As previously stated, the transmitted wireless signals should depend on some technical parameters, regulations and restrictions. These parameters determine the criteria to identify the wireless signals. For instance, to simply indicate, some parts of the frequency spectrum are reserved for certain types of communication technologies and the bandwidth occupation for each signal type is also defined by regulations.

The tree based signal identification algorithm has an inference mechanism depending on the common features of the signals. The proposed methodology is not based on the assumption that the expected signal is known and the certain features of the detected signal is compared with what expected, but all kind of signals can be encountered. Therefore, the algorithm that constituted the core of the methodology is forced to have a common framework to decide on the type of the signal. This common framework eliminates other types of signals depending on the expected values of the common features of wireless communication technologies and assures the match with the unique features of identified signal – if there is any, by crosschecking with parameters defined by specific wireless communication technology.

Adding up the common distinctive properties of signals, the identification tree can be formed in an appropriate manner. Sequence of criteria on the decision tree which will be used for signal identification is the most important part to decide. It is required to put a list of features and characteristics of the wireless signals to come up with the criteria that will be used for discriminating the type of the signal. Then, taking the whole set of criteria into consideration, elimination to reach to the criterion to put at the top of the tree will be done by finding the criterion which has most different values on the signal types that will be identified. Then, the same sequence is repeated for remaining criteria. If two or more criteria are unique in the same level, the selection is made depending on the period of time that is required to extract the feature from the signal. Shorter extraction time means that the criteria will be located in a higher place on the decision tree.

Finally, the proposed system has the capability of identifying unclassified signals. If a signal could not be set to a place through the branches of the decision tree, the signal will be reevaluated in such a way that the branch of the tree that takes the signal out of the tree will be ignored and an estimation technique will be applied to decide the signal type.

4. DESCRIPTION OF DEVELOPED APPLICATION

The main purpose of this application is to identify wireless signals indoor, outdoor, close or away from the base stations. The solid definition of wireless technologies enables us to infer distinct features related to the transmitted signal. Identification of wireless communications signals depends on the recorded communication data in the environment where secondary user will share with the primary users. This communication data may be consisting of set of complex numbers (I/Q Data) which carry the frequency, phase and amplitude information or just the spectral data that carry information about the power levels of the signals in the frequency spectrum. The application is developed to run on spectral data taking these criteria into consideration: a) computational simplicity, b) limitations of equipments and c) strictly defined regulations in frequency domain for wireless communications systems which constitute main parameters for signal identification.

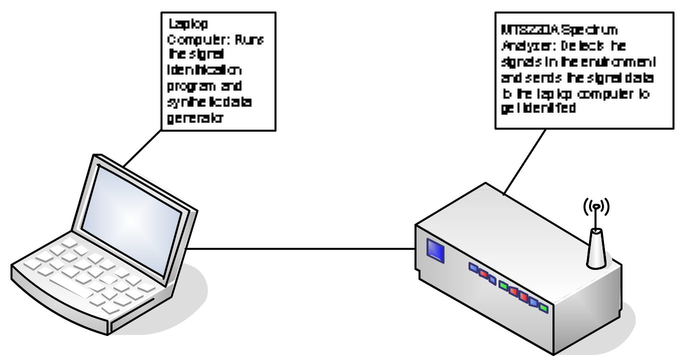
Therefore the developed software works on spectral data and spectral characteristics of wireless signals are used for wireless signal identification; the decision tree simply constructed depending on signal bandwidth and center frequency and these parameters are estimated without any pre-requisite, expected bandwidth and center frequency (regulated by FCC) information is used only for signal classification. Besides single signal identification, the signal identification application is also capable of identifying multiple signals occupying given frequency spectrum. Information about the carrier numbers of multiple carrier signals (e.g., multi-carrier CDMA) and information about adjacent channel interference are also provided. Developed application also informs the user if the signal has low SNR value or not. Extracted signal information through identification process can be seen in table 1.

4.1 Details of Demonstration Setup

The setup mainly consists of two parts: Hardware components and software components. Hardware components are: 1-) Hand held spectrum analyzer: BTS Master MT8222A of Anritsu Co. (details of the equipment can be found in table 2) to capture wireless radio signals in the environment 2-) Laptop PC, to record the captured spectral data and to run the identification software 3-) Fire wire cable to connect the laptop computer and hand held spectrum analyzer for immediate data recording. Software components of the demonstration setup are: 1-) the software running on the BTS Master to detect and record wireless radio signals 2-) Master Tools ™ software of Anritsu Co. to record the spectral data to the laptop computer and 3-) signal identification software running on laptop computer.

Signal Properties	What is the bandwidth of the detected signal? What is the carrier frequency of the detected signal? Waveform Information: Does the signal belongs to one of the current wireless technologies or not? If belongs to a technology which one? For instance GSM, IS-95 or WLAN etc. What is the signal single-carrier or multi-carrier signal? Power levels of the signals identified (multiple signal power levels for certain measurements) Adjacent channel interference information.

Table 2 – Detected Signal Properties to be Displayed



First the BTS Master is connected to the computer via fire wire cable and initialized to the frequency spectrum that the spectral data is expected to be recorded. Then the spectral data is recorded to computer using Master Tools ™ software. After the spectral data is recorded, it firstly converted to appropriate format and then used as input to the signal identification software.

4.2 Signal Identification Software

Signal detection techniques do not fully comply with identification requirements; some of them are not applicable with only frequency information (e.g. cyclostationary feature detection). Energy detection may seem to be a solution however, detecting a signal via using thresholds in general does not bring enough information (possibility of insufficient sample leftover through the threshold for accurate bandwidth and center frequency estimation) besides the possibility of miss detection or false alarm is high.

Frequency Range	100 kHz to 7.1 GHz
Tuning Range	9 kHz to 7.1 GHz
Tuning Resolution	1 Hz
Frequency Span	10 Hz to 7.1 GHz plus 0 Hz (zero span)
Sweep Time	Minimum 100 ms swept, 10 µs in zero span
Sweep Time Accuracy	± 2% in zero span
Sweep Trigger	Free run, Single, Video, External
Resolution Bandwidth	(-3 dB width) 10 Hz to 3 MHz in 1-3 sequence ± 10%, 8 MHz demodulation bandwidth.

Table 2 – MT8220A Properties

From the measurement view of point we know that we will deal with a finite number of discrete samples of N and because that the equipment used has a dynamic range, it should be possible to record the spectral data, over a minimum of the power level namely over a signal base. Therefore estimating the signal base accurately and applying a band of threshold instead of a single threshold value gives the opportunity to collect as much sample as can be about the signals over the spectrum and make an accurate decision on bandwidth and center frequency. The important issue is how to choose the threshold band length. At this point, this range of the length can be computed depending on the fluctuations of samples over the spectrum. The level of the fluctuations is given by the standard deviation of the samples recorded for the given frequency spectrum. If the fluctuations are high (figure 2.a), base level will be higher to get maximum information about these fluctuations. If the fluctuations are lower (figure 2.b), then base level can be lower. If the total number of samples are N and *x(n)* represents the spectral signals, the average of the samples and the standard deviation are given by:

$$\overline{x} = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{x_1 + x_2 + \cdots + x_N}{N}$$

And the standard deviation is given by:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}.$$

The threshold value is calculated by:

T = k * s

For some cases the standard deviation may exceed the mean power level or can be so high that some spectral information can be lost therefore the coefficient is selected to be 1 = k > 0 in general. It can be iteratively computed depending on the data and can be optimized.

4.3 Sample Case

In this section, detection results using the threshold approach of energy detectors and proposed methodology is compared. An example measurement result can be seen in Figure 3. Here more than ten signals can be detected using energy detection methodology. The false alarm – missed detection results starting from a minimum level of threshold through the maximum one is simulated in figure 4. Then the standard deviation of the samples is computed and the threshold band length is calculated. Again the false alarm – miss detection rate is computed for the threshold band. The resultant value plotted as a single point in figure 4. It is clear from figure 4 that the proposed approach has better false alarm – miss detection figures than any of the thresholds that can be applied.

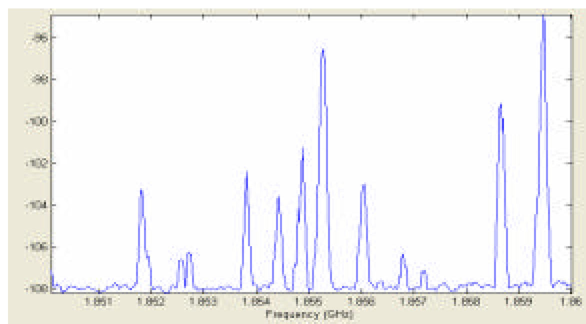


Figure 3 – Sample Spectral Measurement

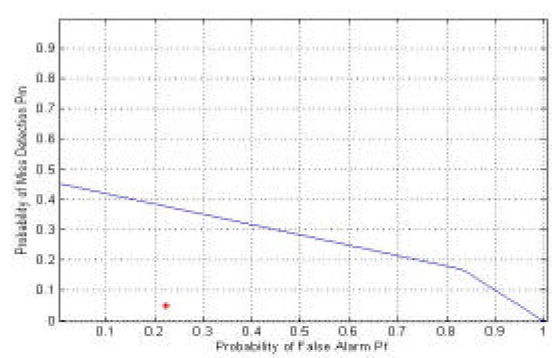


Figure 4 – Simulation Results: Energy Detector Threshold vs. Proposed Approach

The speed of the identification of the signal is another important aspect. It is possible to design a system with high precision prediction rate by monitoring the frequency band longer or by increasing the resolution bandwidth and investigating it in more detail. However, it is important to remember here that the concern is to allocate some bandwidth in a specific period of time, in a specific area to a secondary user without affecting the communication traffic of the primary users. That needs to be handled as fast as possible with as less error as possible. The connection of the secondary user to the network must not be delayed and the communication must be established securely. The simple tree structure algorithm and the modular structure of signal identification software bring the required agility and accuracy for efficient spectrum sensing applications.

4.4 Sub-modules of Signal Identification Software

Signal identification software acquires spectral data recorded with BTS Master of Anritsu as input. When the input acquired properly, signal base is computed so that the signal samples higher than this level will be inspected for possible wireless signal occupancy (Signal Base Finder Module). Details of this procedure are given in previous sections. Secondly the spectral data is separated and grouped depending on their neighborhood, relevant to the base level computed (Signal Distinguisher Module). After the data groups constituted, bandwidth and center frequency estimation is conducted on each data set (Bandwidth and center frequency estimation module). The resultant estimated bandwidth and center frequency values are compared with FCC regulations; the decision is made about the type of the signal and the resultant signal information outputted to be displayed (Signal Classifier – Identifier Modules).

As the output, inspected spectral data plotted to a graph with identified signals center frequencies marked. The identified signals with their center frequency and characteristic information (number of carriers, interference, low SNR etc.) are also listed at the user interface. An example of user interface is given in figure 5.

5. CONCLUSION

Identification of wireless signals requires a more sophisticated approach regarding to detection systems. A simple statistical methodology to estimate the signal base; depending on the standard deviation of the spectral data is proposed. Simulation results indicated that better false alarm – miss detection rates than energy detectors are achieved with the minimum complexity of $O(n)$. Moreover, the proposed approach gave the opportunity to collect enough samples of detected signals for accurate bandwidth and center frequency estimation. However, the proposed methodology produces successful results for the spectral data with flat signal base. An improvement is required for the data with unstable signal base.

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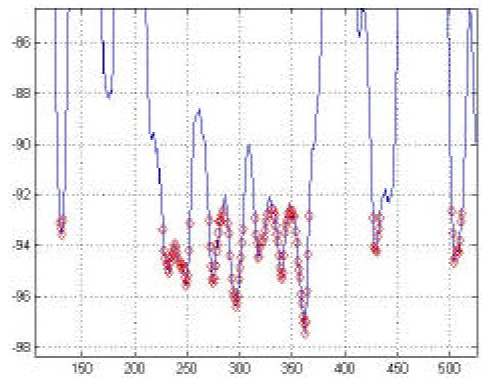

Figure 2.a

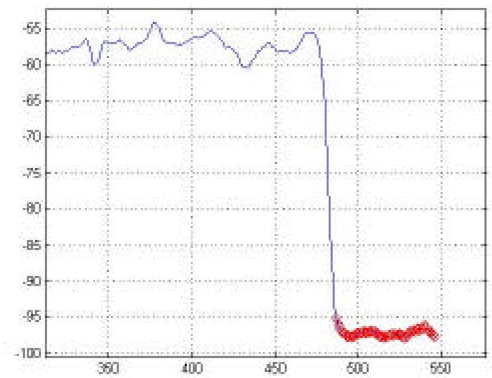

Figure 2.b

Figure 2 – Signal Base Estimation

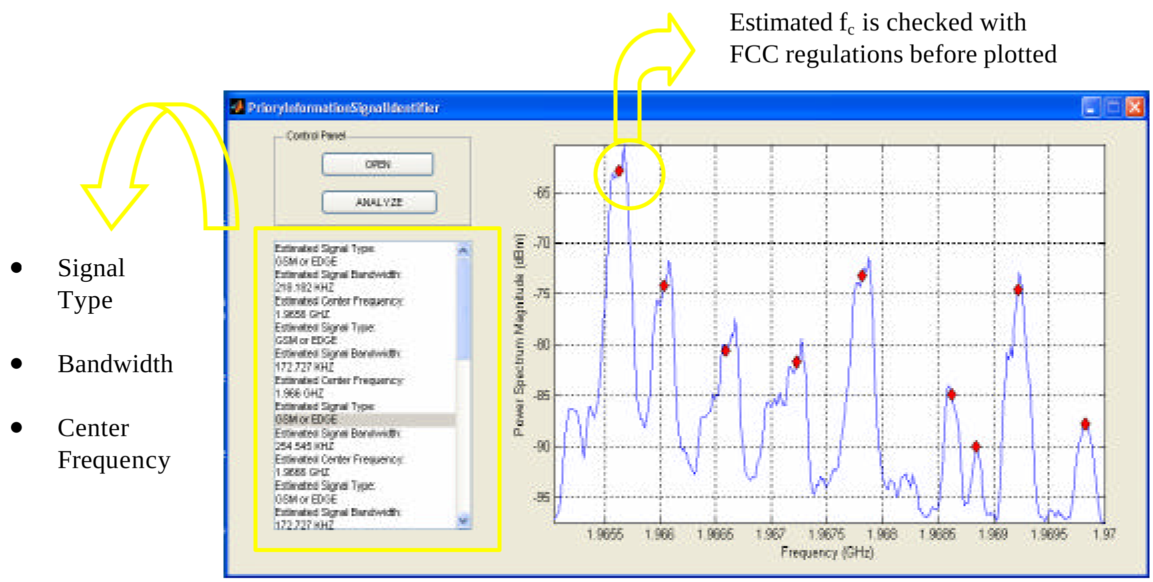

Figure 5 – Signal Identification Software User Interface

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