IJCSE International Journal of Computer Sciences and Engineering Open Access
Survey Paper Volume-2, Issue-8 E-ISSN: 2347-2693

Sensing of Spectrum Holes in Cognitive Radio Networks: A Survey

Navdeep Kaur Randhawa[1*] and Avtar Singh Buttar[2]

[1*]*Department of Electronics and Communication, Punjab Technical University, India*
[2]*Department of Electronics and Communication, Punjab Technical University, India*

www.ijcaonline.org

Received: 27/07/ 2014 Revised: 04/08/ 2014 Accepted: 24 /08/ 2014 Published: 31 /08/ 2014

***Abstract*—** Cognitive Radio (CR) has risen as a tempting solution to the problem of spectral inefficiency as it performs sensing of the radio environment, sharing it without harmful interference to Primary Users (PU) and quickly quitting the frequency band if the corresponding licensed user emerges. Spectrum Sensing is the most crucial task for the establishment of cognitive radio based communication mechanism. Challenges related to spectrum sensing are discussed and different sensing techniques are surveyed in this paper along with the analysis of their advantages and disadvantages.

***Keywords*—**Cognitive Radio, spectrum sensing techniques, sensing challenges

I. INTRODUCTION

With the constant increase in demand for spectrum due to rise in the availability of new services and technological advances in the field of wireless communication the need to optimize the utilization of spectrum is felt all the more. However conventional method of spectrum allocation to licensed user is very inflexible, where licensed user has exclusive right to operate in that allocated frequency band. With this scheme most of useful spectrum is already allocated so it is hard to accommodate new services or to improve existing services.

As a fact, in most licensed bands the actual percentage of spectrum usage is under 50%, or in some cases, in the order of 10%. Thus, spectrum access is found to a more significant problem than physical scarcity of spectrum [4] i.e. there are a lot of spectrum holes or white spaces, which are defined as a set of frequency bands assigned (licensed) to a Primary User (PU), but, at a particular time and specific geographic location, not being utilized by that user. To get rid of this situation, Cognitive Radio (CR) arises to be an alluring solution as it is capable of resolving the spectral crowding problem by introducing the opportunistic usage of frequency bands that are not heavily occupied by licensed users at that particular moment i.e. it helps in 'Bandwidth Harvesting'. This observation leads us to a key idea that the spectrum utilization can be drastically increased by allowing Secondary Users (SU's) to access to the spectrum holes that are unutilized by the PU at certain time and space. The main capabilities implemented by a CR user to fulfill its responsibilities are: Identification of current opportunities for spectrum (or channels) utilization by Spectrum Sensing, Spectrum Decision and Spectrum Sharing/ Analysis and then the ability to vacate that spectrum (or channel) if a licensed user wants to use that resource (Spectrum Mobility).

Amongst all the important function of CR is learning about the radio environment through sensing i.e. detecting unused spectrum, sharing it without harmful interference to other users and quickly quitting the frequency band if the corresponding primary radio emerges. Thus, spectrum sensing is the most crucial task for the establishment of cognitive radio based communication mechanism. This paper briefs the challenges faced while accomplishing the sensing task and also reviews the spectrum sensing techniques used to efficiently detect the spectrum holes and sense the presence of PU.

The paper is organized as follows: in section II challenges related to sensing are discussed and then section III reviews the spectrum sensing techniques. Section IV proves comparison of the sensing methods with a brief overview of their advantages and disadvantages. Conclusion is presented in Section V.

II. SPECTRUM SENSING CHALLENGES

Spectrum sensing constitutes one of the most important components of the CR operation. The main issues in this area are:

A. Hidden Node Problem

The fading effects of the wireless channel play a negative role and ends up in creating the well known 'hidden node' i.e. hidden primary user problem. It arises when the spectrum sensing terminal (CR receiver) is deeply faded with respect to the transmitting node while having a good channel to the receiving node. The spectrum sensing node then senses a free medium and initiates its transmission, which produces interference on the primary transmission. Thus, fading here introduces uncertainty regarding the estimation problem.

B. Limited Sensing Ability

Cognitive radio has limited ability to detect the spectrum holes as it has only a basic 'sense of hearing' which means it has to detect its multidimensional environment with only a

Corresponding Author: *Navdeep Kaur Randhawa*

single sense. Many queries related to the sensing ability and performance in wide bandwidths has come up for which advanced techniques are needed to overcome the problem of sensing very wide bandwidths reliably and rapidly.

C. *Wideband Sensing*

One of the main concerns in spectrum sensing is how to set the boundaries of the spectrum desired to be sensed. Instead of very wide band detection, limited spectrum can be used for spectrum sensing as while working in limited spectrum, received signal can be sampled at or above Nyquist's rate with current technology. Moreover, the computational difficulties experienced in wide band detection can be restricted to a reasonable level as it helps in avoiding the expensive analog front-end required for the detection of very wide spectrum. Considering the issues, the regulatory agencies should allocate spectrum bands for different types of cognitive radios depending on the spectrum range that they work in.

D. *Sensing Time*

As a matter of fact, the PU's can use their licensed frequency bands any time, thus to increase the capacity of the spectrum and avoid interference, spectrum holes must be detected as swiftly as possible to accommodate the CR users. This requires the spectrum sensing algorithm to perform its detection task within limited time duration. Also the frequency of sensing must be taken into account as it needs to sense very often in order not to miss any opportunity.

E. *Multiuser environment*

The environment in which CR based systems work, generally consists of multiple unlicensed and licensed users. The existence of multiple Secondary Users(SU) causes interference as a challenge in spectrum sensing to other SU's in the environment that is expected to make it difficult to sense primary users reliably. To overcome this problem, a few aspects of cooperation in spectrum sensing must be considered such as the distributed information (transmitted power, frequency of other users, location). Second, the transmissions of other CR users may prevent a specific CR user from detecting the activity of a primary transmitter and lead the CR user to regard the primary user transmission as noise. This leads to degradation in sensing accuracy.

F. *Mobility*

Spectrum sensing aims to provide a map of the spectrum in CR vicinity. As a result, efficient spectrum decision techniques need to be used. However, if a CR user moves, the spectrum allocation map may change rapidly so, the spectrum allocation map constructed by the sensing algorithm may become obsolete with high mobility. Consequently, the CR user may need to perform spectrum sensing as they change location. This necessitates an adaptive spectrum sensing technology that is responsive to the mobility of the CR user.

G. *Security*

From the PU viewpoint, CR users can be regarded as malicious devices that eavesdrop on the channel that is being used by the licensed user for transmission which means that the spectrum sensing techniques resemble eavesdropping attacks. But in order to preserve the privacy of the PU the sensing techniques need to be carefully designed. Since each PU owns the particular spectrum, the traffic flowing through this spectrum needs to be protected. Sensing techniques, however, demand the knowledge of the existence of licensed users for efficient operation but they ought to be designed in such a way that they are aware of the existence of the ongoing traffic but cannot determine its content.

III. SPECTRUM SENSING TECHNIQUES

Spectrum sensing is the ability to measure, sense and be aware of the parameters related to the radio channel characteristics, availability of spectrum and transmit power, interference and noise, radio's operating environment, user requirements and applications, available networks (infrastructures) and nodes, local policies and other operating restrictions.

Sensing is done across Frequency, Time, Geographical Space, Code and Phase.

- Its outcomes serve as an input to spectrum decision and sharing modules.
- Motivation here is to detect the spectral holes in the spatio-temporal domain
- It is also called 'spectral sniffing'

The following section presents a survey of various spectrum sensing methods from the literature, which has been designed to resolve the challenges experienced while sensing at the CR receiver.

A. *Energy Detection based spectrum sensing*

In this method presence or absence of a primary user signal is determined by just calculating energy of the received signal and comparing it with known threshold T which is derived from noise statistics [1], [6]. This is known to be the simplest and the most generic method of PU detection. It even does not require a priori knowledge of PU signal details such as transmitted power, carrier signal frequency, and center frequency, type of modulation, bandwidth and frequency hopping sequence. Due to these advantages energy detection method is a most popular spectrum sensing method in cooperative sensing [5]. Fig 1 shows the model for energy detection method.

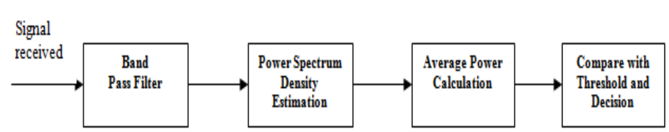

Fig 1: Energy detection based spectrum sensing method

The received signal is passed through band pass filter of the bandwidth W and the average power is calculated over that frequency range as in (1) [10].

$$P_{awg} = \sum_{n=1}^{N} |x(n)|^2 \quad (1)$$

Finally the output signal is then compared with a known threshold level T in order to decide whether a signal is present or not in that frequency band. Analytically, this sensing method can be reduced to a simple hypothesis test given in (2)

$$y(n) = \begin{cases} w(n), & H_0 \\ w(n) + x(n), & H_1 \end{cases} \quad (2)$$

Where, y (n) is the sample to be analyzed at each instant k and w(n) is the noise.

Then decision is made according to following conditions (3) where the threshold value is set to be fixed or variable based on the channel conditions.

$$\begin{aligned} &H_0 \text{ (primary user present) when, } P_{awg} < T \\ &H_1 \text{ (primary user present) when, } P_{awg} > T \end{aligned} \quad (3)$$

Though being simple and easy to implement technique, it experiences challenges like the selection of the threshold for detecting primary users, inability to differentiate interference from primary users and noise and poor performance under low SNR values. When the performance of conventional technique was reviewed it shows a great deterioration especially in low SNR environments. Also, the inappropriate setting of the detection threshold leads to a significant decline in the performance of detection. So, energy detection based optimal threshold scheme was proposed. An optimal threshold level based on the tradeoff between misdetection probability and false alarm probability P_f is derived by developing an adaptive threshold factor with optimal algorithm in order to combat the noise uncertainty which is compatible with the real world communications and that allows gaining better spectrum sensing performance especially in low SNR.

B. Cyclostationary Feature detection based spectrum sensing

Cyclostationary feature detection based spectrum sensing is based on the fact that when a transmitted signal is modulated with a sinusoidal carrier, cyclic prefixes code (as in OFDM) or hopping sequences (as in CDMA), cyclostationarity is induced i.e. mean, autocorrelation showing periodic behavior in primary user signal are the features which are exploited in a Cyclostationary Feature Detector that measures a signal property called Spectral Correlation Function as shown in Fig 2 [2], [8]. It can differentiate noise from primary user's signals considering the fact that noise is Wide-Sense stationary and is assumed to have no noise correlation [10]. Cyclostationary sensing performs better than Energy Detection because of its noise rejection ability. This occurs because noise is totally random and does not exhibit any periodic behavior.

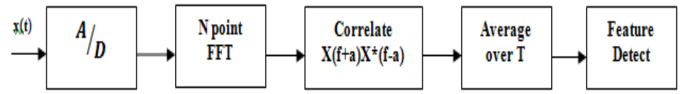

Fig 2: Cyclostationary Feature detector

However, it is highly complex which results in high cost and requires long sensing intervals compared to energy detection technique.

C. Matched Filter based spectrum sensing

Matched filtering works better if it has a perfect prior knowledge of licensed users' features such as bandwidth, frequency, modulation type, etc. to demodulate received signals [11]. Therefore it needs dedicated signal receivers for each signal type that leads to the implementation complexity and large power consumption as various receiver algorithms need to be executed for detection. Matched filter is generally a linear system or filter whose operation can be represented as in (4)

$$y(n) = \sum x(n).h(n-k) \quad (4)$$

where, x(n) is vector of unknown signal and h(n) is impulse response of matched filter which is matched to reference signal to maximize SNR

D. Radio Identification based spectrum sensing

In this sensing method very low SNR signals with relaxed information on the signal parameters are being detected by determining the transmission technologies used for primary users. Such identification of technologies used by primary users enables cognitive radio with a higher dimensional knowledge as well as providing higher accuracy. For sensing using radio identification method, several features of received signal are extracted and then they are used for selecting the most probable primary user technology by employing various cleassification methods [8], [9]. Some features such as energy detected and its distribution across the spectrum, channel bandwidth and its shape are used as reference features.

E. Waveform based sensing

With the knowledge of known pattern such as preambles sequence (transmitted before each burst), mid-ambles sequence (transmitted in middle of burst or time slot), regularly transmitted spreading sequences, pilot patterns etc. waveform based spectrum sensing is performed by correlating the received signal at CR receiver with a known copy of itself. It outperforms energy detection in terms of reliability and convergence time [15]. Performance of this sensing technique increases as the length of the known signal pattern increases. The waveform-based decision metric can be obtained as in (5):

$$M = \mathrm{Re}\left[\sum_{n=1}^{N} y(n) * s(n)\right] \quad (5)$$

Where y(n) is the received signal

In absence of primary user: y(n) = w(n) (6)

In presence of primary user: y(n)=s(n)+w(n) (7)

When PU absent, the metric value M becomes,

$$M=\text{Re}[\sum_{n=1}^{N} w(n) * s(n)] \quad (8)$$

When PU present, the metric M becomes,

$$M= \sum_{n=1}^{N} |s(n)|^2 + \text{Re}\,[\sum_{n=1}^{N} w(n) * s(n)] \quad (9)$$

Decision on the presence or absence of a primary user signal can be obtained by comparing the decision metric *M* with a fixed threshold T.

F. Cooperative spectrum sensing

For cooperative spectrum sensing in a multi user Cognitive Radio Network (CRN) where multiple CR users cooperate in sensing the channel problem of high sensitivity requirements is alleviated [12]. Cooperative sensing holds the advantage of reducing the probability of false alarm and misdetection and decreasing the sensing duration. It is capable of solving the problems that arise in spectrum sensing due to uncertainty in noise, shadowing and fading. It can also solve hidden node problem. But, the requirement of system synchronization and the need to perform sensing at periodic intervals come up as the shortcomings. As shown in Fig 3, according to the level of cooperation, they can further be classified into three regimes [5], [7], [12].

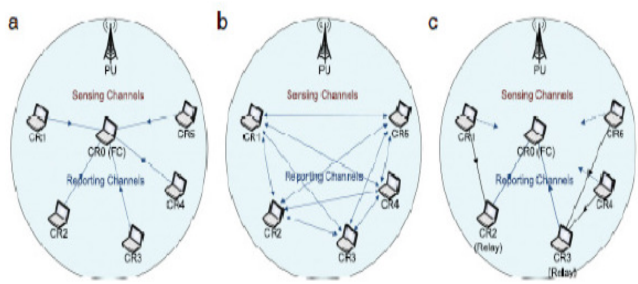

Fig 3: Cooperative sensing techniques: **a**-Centralized Coordinated, **b**-Decentralized Coordinated, and **c**- Decentralized Uncoordinated

1) Decentralized Uncoordinated techniques

Fig 3(c) shows the networks using this technique do not have any kind of cooperation among the CR nodes which means that each CR user will independently detect the channel, and if a CR user detects the primary user it would vacate the channel without informing the other users. Uncoordinated techniques are fallible in comparison with coordinated techniques [5]. Therefore, CR users that experience bad channel realizations detect the channel incorrectly thereby causing interference at the primary receiver.

2) Centralized Coordinated techniques

In such networks one CR that detects the presence of a primary transmitter or receiver, informs a CR controller which notifies all the CR users in its range by means of a broadcast control message. CR users independently detect the channel and inform the CR controller which then notifies all the CR users. Fig 3(a) shows that CR controller (Fusion Center) collects information from CR devices determines the available spectrum and broadcasts the information of availability or non-availability of spectrum to other CR or directly controls the cognitive traffic [5].

3) Decentralized Coordinated techniques

This type of coordination implies building up a network of cognitive radios without having the need of a controller (base station or central unit). Fig 3(b) shows that in this sensing method the CR's exchange information among across each other but makes their own decision as to which part of spectrum they can use. This technique eliminates the need for backbone controller which reduces the cost significantly compared to centralized sensing [5].

G. Multitaper spectrum estimation

In this estimation technique the last N samples are collected in vector form and are represented in Slepian base vectors. This has been done knowing the fact that a Fourier Transform of Slepian vector has the maximal energy concentration in the bandwidth F_c-W to F_c+W under finite sample size constraints. Thus, cognitive user can easily identify the spectrum opportunities in the given band by exploiting this feature. Multitaper Estimation uses multiple prototype filters which limit its better performance for small sample spaces since the computational complexity increases with large number of samples [14].

H. Spectral Feature spectrum sensing

This is a spectrum sensing technique based on correlating spectra for detection of television (TV) broadcasting signals [18]. The basic strategy is to correlate the periodogram of the received signal with the selected spectral features of a particular TV transmission scheme, either the National Television System Committee (NTSC) scheme or the Advanced Television Standard Committee (ATSC) scheme with that of the received signal, and then to examine the correlation for decision making. It is shown that according to the Neyman-Pearson criterion, this spectra correlation-based sensing technique is asymptotically optimal at very low SNR and with a large sensing time. The PSD of the observations is estimated through by using the periodogram, i.e., the squared magnitudes of the n-point discrete-time Fourier transform (DFT) of the n-point received signal, denoted by $S_Y^{(n)}(k)$, k=0,1,……,n-1. On the other hand, the n-point sampled PSD of the signal under detection is known a priori at the receiver.

$$S_X^{(n)}(k) = S_X(2\Pi k/n) \quad (10)$$

To detect the presence of a TV (NTSC or ATSC) signal, we perform the following test:

$$T_n = \frac{1}{n}\sum_{k=0}^{n-1} S_Y^{(n)} S_X^{(n)}(k) \underset{H_0}{\overset{H_1}{\gtrless}} \gamma \quad (11)$$

Where, γ is the decision threshold.

Now, if the spectra correlation between $s_x^{(n)}$ and $s_Y^{(n)}$ is greater than the threshold then H1 i.e. presence of the signal of interest otherwise H0 i.e. absence of the primary signal is concluded. Spectral feature based detection is a very reliable technique to sense spectrum at very low SNR region in contrast to other techniques like energy detection, matched filtering based detection except the weakness of prior knowledge requirement about PU signal spectral features for correlation.

I. Wavelet based spectrum sensing

In this spectrum sensing technique wavelets are used to detect sub-band edges in power spectrum density of wideband channel where, edges correspond to transition from one occupied band to vacant band or vice-e-versa. Then the characteristics of the spectrum can be defined as occupied or vacant, using this technique the detected information [13]. As known noise is primarily of high frequency and the signal of interest is of low frequency, the wavelet transform decomposes the signal into approximation (low frequency) and details (high frequency) coefficients, the detail coefficients containing much noise. The Fig 4 is an illustration of the wavelet packet decomposition tree.

Where, An denotes High Pass filter and Dn denotes a Low Pass filter, n: Level of decomposition.

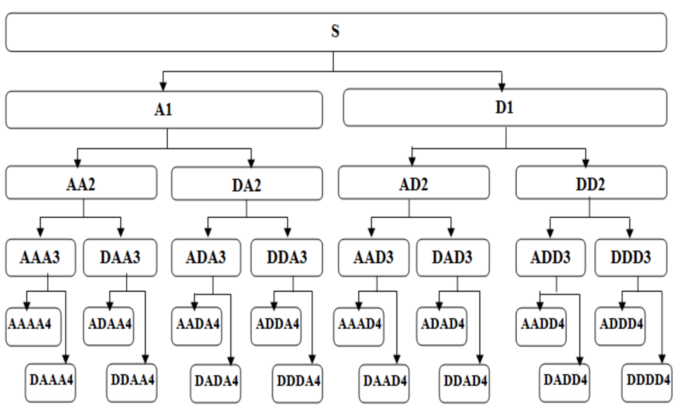

Fig 4: 4-level Wavelet Packet Decomposition Tree

It splits both low pass and high pass sub-bands at all scales in the filter bank approximation and implementation. Hence it is suitable to finely identify the information in both high and low frequency bands and thus is an ideal processing tool for non-stationary time-variable signal.

J. Entropy based spectrum sensing

Entropy based spectrum sensing technique uses likelihood ratio test which examines the presence or absence of the primary user by comparing the empirical entropy of the received signal to a suitable threshold [16]. The underlying concept is such that, for a given signal power, the entropy of a stochastic signal is maximized if it is Gaussian. However, if the received signal contains the digitally modulated component, its entropy will be reduced. The likelihood ratio test for detecting the primary user compares the empirical entropy of the received signal to a suitable threshold. This method gives the merit of no prior knowledge on primary user's signal characteristics and less computational complexity.

When entropy of the sensed signal is estimated in the frequency domain with a probability space divided into fixed dimensions [17]. It proves to be robust against noise uncertainty compared to the traditional detectors such as matched filters, energy detectors, and even cyclostationary detectors whose performance deteriorates rapidly at low SNR. Also the sample size requirement is significantly reduced compared to an energy detector.

IV. Comparison Of Different Spectrum Sensing Techniques

The comparison of shown in Fig 5 depicts the high complexity of matched filter based detection along with high accuracy compared to the least complex energy based detection which exhibits least accuracy compared to other spectrum sensing approaches.

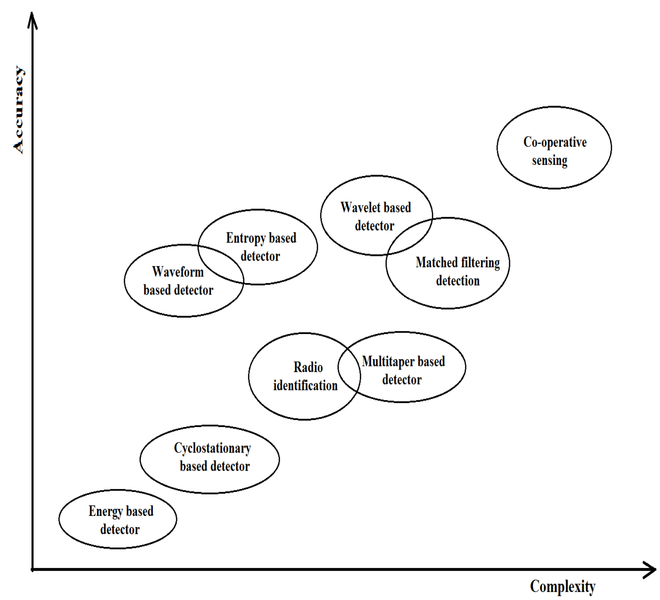

Fig 5: Comparison of various sensing methods in terms of their accuracy and complexity

Waveform based sensing is more robust than energy detector and cyclostationary based methods because of the coherent processing. While sensing techniques based on entropy and wavelet decomposition exhibit a balance between the two parameters i.e. good accuracy with moderate complexity.

The cooperative sensing techniques provide high detection accuracy along with very high complexity but these techniques are generally preferred over CR networks rather than a single radio thus, complexity can be accepted as long as accurate detection is received.

Table 1 shows study of advantages and disadvantages of various spectrum sensing techniques.

TABLE 1: Study of various existing spectrum sensing techniques

S.No.	Spectrum Sensing Method	Advantage	Disadvantage
1.	Energy based	Low implementation and computational complexity, no knowledge of PU required	Performance highly vulnerable to noise uncertainty. Inability to differentiate between modulated signals, noise, and interference. Selection of threshold is hard.
2.	Matched Filtering based	Optimum performance in terms of observation time and optimal detection in stationary Gaussian noise when the information of the PU signal is known to CR user.	Requires full PU knowledge, which if inaccurate leads to poor sensing performance. Has high power consumption and implementation complexity
3.	Cyclostationary Feature Detection	Robust to interference and has noise rejection ability. Can differentiate between the noise energy from modulated signal energy and detect the signals with low SNR.	Involves high computational complexity, long observation time and needs the prior knowledge of the PU's.
4.	Radio Identification based	Ability to detect low SNR signals	Requires the knowledge about the transmission technologies of the PU's
5.	Waveform based	Low complexity, outperforms energy detector method in terms of reliability and convergence time	Requires information about the PU signal waveforms
6.	Multitaper based	Easy and fast identification of signals with moderate accuracy	High complexity
7.	Spectral Feature based	Reliable sensing at very low SNR region	Prior PU knowledge required
8.	Wavelet based	Better and fast sensing, high resolution outputs	Computational complexity increases with the increase in decomposition level
9.	Entropy based	Low complexity, robust to noise uncertainty (when computed in frequency domain), no prior PU knowledge	Vulnerable to noise uncertainty (when computed in frequency domain)
10.	Cooperative sensing	Solve hidden primary user problem, noise uncertainty and uncertainty due to multipath fading. Reduces the sensitivity requirements and overall detection time which improves the agility of detection.	High complexity and cost, requires system synchronization.

V. CONCLUSION

Spectrums sensing is the key function in the cognitive radio networks. The challenges associated with the task of sensing are discussed and a handful of spectrum sensing techniques are reviewed in this paper along with an overview about their advantages and disadvantages.

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AUTHORS PROFILE

Navdeep Kaur Randhawa

is a PG student in the Department of Electronics and Communication at Punjab Institute of Technology (PTU Main Campus), Kapurthala, Punjab, India. She obtained B.Tech (Electronics and Communication) from Punjab Technical University. Her research area interests includes wireless communication networks and cognitive radio networks.

Avtar Singh Buttar

is presently working as Associate Professor, PunjabTechnical University Jalandhar (Pb.) India. He obtained his B.E. in Electronics & Comm.Engg. from Punjab University in 1989. He qualified his Masters Degree in 1995 from National Institute of Tech., Kurkshetra. His research interests include Wireless Communication and Computational Intelligence.

