LOCATION BASED SPECTRUM SENSING IN COGNITIVE RADIO SYSTEMS

by

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ABSTRACT

LOCATION BASED SPECTRUM SENSING IN COGNITIVE RADIO SYSTEMS

Cognitive radio is a promising solution to the spectrum utilization problem in time and space. One of the most critical points of cognitive radio is spectrum sensing. A reliable sensing is important for not disturbing the primary user and utilizing the spectrum usage. In this thesis energy detection algorithm is selected because of its ease of implementation, low cost and low computational complexity. Secondary user knows the location information of the primary users. A central database which is called Radio Environment Map (REM) stores the location information of the primary users, and on which frequencies each primary user operates. The REM calculates the distances between the primary users and the secondary user. Using the distance information and the inverse proportion relation between distance and signal to noise ratio (SNR), the secondary user decides on which sequence it will sense the primary users in order to maximize its signal to noise ratio. The secondary user senses the primary users beginning from the closest to the furthest, until it finds an empty channel. It stops sensing when it finds a non transmitting primary user. Using this sequence it will maximize average SNR and increase sensing performance. The error capacity of this method is also analyzed. Performance of proposed method under erroneous location information is measured with simulations. Another method is proposed when the maximum interference distance of secondary user is known. By this new information the CU can use the channels of the PUs which are outside the interference range without sensing them. The final proposed algorithm is cooperation of two cognitive users using the distance information of primary users. Each cognitive user starts sensing from the closest PU to itself, and stops sensing when one of them finds an empty channel or the next closest PU that is closer to the other CU.

ÖZET

YER BİLGİSİ İLE BİLİŞSEL RADYODA SPECTRUM SEZME

Bilişsel radyo, zamanda ve mekanda spektrum kullanım değerlendirilmesi için gelecek vaadeden bir çözümdür. Bilişsel radyonun en kritik noktalarından biri de spektrum sezimidir. Güvenilir bir spektrum sezimi, birincil kullanıcıları rahatsız etmemek ve spektrum kullanımını değerlendirmek açısından önemlidir. Bu tezde uygulama kolaylığı, düşük maliyeti ve düşük hesaplama karmaşıklığı nedeni ile enerji sezim yöntemi seçilmiştir. İkincil kullanıcı birincil kullanıcıların yer bilgilerine sahiptir. Radyo çevre haritası adı verilen bir merkezi veritabanı birincil kullanıcıların yer bilgilerini ve her birinin yayın yaptıkları frekans bilgilerini depolar. Radyo çevre haritası birincil kullanıcılar ile ikincil kullanıcı arasındaki mesafeleri hesaplar. İkincil kullanıcı bu mesafe bilgisini ve mesafe ile SNR arasındaki ters orantı bilgisini kullanarak ortalama SNR'ı maksimize etmek için birincil kullanıcıları hangi sıra ile sezmesi gerektiğine karar verir. İkincil kullanıcı, boş bir kanal bulana kadar en yakındaki birincil kullanıcıdan başlayarak en uzaktakine doğru sırayla sezer. İletim yapmayan bir birincil kullanıcı kanalı bulduğunda sezmeyi bırakır. Bu metodun hata kapasitesi de analiz edilmiştir. Sunulan yöntemin hatalı lokasyon bilgileri ile verdiği performans ölçülmüştür. Maksimum girişim mesafesinin bilindiği bir başka bie metod da sunulmuştur. Bu yeni bilgi ile bilişsel kullanıcı maksimum girişim mesafesinin dışında kalan ikincil kullanıcıların kanallarını sezmeye gerek olmadan kullanabilir. Sunulan son metod da birincil kullanıcıların yer bilgilerini kullanarak iki bilişsel kullanıcının işbirliği yapmasıdır. Her bilişsel kullanıcı kendisine en yakın birincil kullanıcıdan başlayarak spektrumu sezer ve herhangi bir kullanıcı boş kanal bulduğunda ya da bir sonraki kendisine yakın olan birincil kullanıcı diğer bilişsel kullanıcıya daha yakın olduğunda spektrumu sezmeyi bırakır.

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LIST OF SYMBOLS/ABBREVIATIONS

$d0$	Reference distance at which the path loss is known
g	Channel gain
H_0	Hypothesis saying there is a primary user transmitting data
H_1	Hypothesis saying there is no primary user transmitting data
$h(t)$	Impulse response of matched filter
N	number of samples
n	Path loss component
$n(t)$	Additive white Gaussian noise
PR_d	Received power at distance d
Q_k	Generalized Marcum Q-function
$s(t)$	Transmitted signal of primary user
TW	Time bandwidth product
$x(t)$	Received signal by secondary user
$\overline{x}(k)$	Complex conjugate of $x(k)$
Y	Measured energy of the received signal
γ	Signal to noise ratio
$\Gamma(k)$	Complete gamma function
$\Gamma(k, \tau/2)$	Incomplete gamma function
τ	Threshold value
χ^2_N	Central chi-square distribution with N degrees of freedom
$\chi^2_N(2\gamma)$	Non central chi-square distribution with N degrees of freedom
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BWRC	Berkeley Wireless Research Center
CU	Cognitive User
CR	Cognitive Radio
FCC	Federal communications commission

ID	Interference distance
IEEE	Institute of Electrical & Electronics Engineers, Inc.
PL	Path loss
PR	Received power
PT	Transmitted power
PU	Primary User
REM	Radio Environment Map
ROC	Receiver Operating Characteristics
SDR	Software Defined Radio
SNR	Signal to Noise Ratio
SU	Secondary User
TV	Television
UHF	Ultra High Frequency ($300 - 3000MHz$; $1m - 10cm$)
VHF	Very High Frequency ($30 - 300MHz$; $10 - 1m$)

1. INTRODUCTION

There is an increasing market for wireless telecommunication devices. We can easily see the increasing number of wireless device users and increasing number of wireless communication devices per person when we look around. These devices work on specific frequency bands. Most of the wireless devices, especially the telecommunication devices work on licensed frequency bands. With the increase on consumption of wireless devices and new technologies, the demand on available radio spectrum increases.

The studies show that the licensed radio spectrum is not fully utilized in time and space [1]. Federal Communications Commission (FCC), which is an independent United States government agency, has reported that they pay attention to the spectrum utilization concept [1, 2, 3]. The cognitive radio concept has been introduced for utilization of this valuable natural resource. IEEE has made a group for standardizing cognitive radio concept (IEEE 802.22) for UHF/VHF TV bands.

The cognitive radio proposes the usage of licensed spectrum by unlicensed users whenever it is available. But the cognitive radio users should not interfere with the licensed users and try to find an unused licensed frequency, which is also called a white space. Licensed users have priority of usage of the spectrum. This is why they are called primary users. The cognitive users are also called secondary users. The cognitive users have to detect the presence of the primary users. Cognitive users should also leave the channel as soon as the licensed user starts transmission. There are a lot of ways for detecting the presence of the primary user. Detection of the transmitter is the most commonly proposed method. There are also different methods for transmitter detection. Matched filter is the optimum solution for transmitter detection in cognitive radio, because this method maximizes the signal to noise ratio; but it is not preferred because of its high complexity and requirements on knowledge of the primary signal structure. Energy detection is the most commonly proposed method. It is easy to implement, it does not require primary user signal structure information, it is a cheap solution, etc. But the energy detection method is poor at determination of the source of the signal, which means identification of the signal and noise is not good, especially in low signal to noise ratio and it requires long sensing time which is not preferred by cognitive radio. This will result in low sensing performance, a lot of false alarms and missed detections. But there are many methods proposed for enhancement on energy detection. Feature detection method is another way for transmitter detection. In feature detection method uniqueness of the spectral correlation properties of different signals are used. This method also requires some information about the primary user such as its modulation type, cyclic prefixes etc. Computational complexity of feature detection method is high, so it is not a commonly proposed method [1, 4].

Usually there is assumed to be more than one user in the communication area. In order to increase the sensing performance of the cognitive radio, the secondary users may share their sensing information about the primary users and increase the overall performance. The cooperation of the secondary users has a lot of open research areas. How the cooperation will be performed is a question to be answered. The cognitive users may distribute their sensing information to a central station, or distribute this information to the nearby cognitive users. It has to be decided how much sensing information has to be distributed. There are several ways of combining received sensing information, an appropriate solution shall be chosen.

There are other design issues in cognitive radio. Some methods proposes a central base station and the cognitive users are managed by these base stations, while some methods proposes an ad hoc network for the cognitive radio. The internal communication of the cognitive radio is also another design issue. A pilot channel is usually assumed to be reserved for internal communication of cognitive radio. Cognitive radio can not sense the frequency and make transmission at the same time. A schedule and the amount of time which will be spent for sensing and transmission has to be decided. This is an ongoing process. The cognitive user has to sense and analyze the spectrum continuously. This process is illustrated in Figure 1.1. In the next sections motivation of this thesis is explained, the contribution of this thesis is also described, and finally the organization of the thesis is expressed.

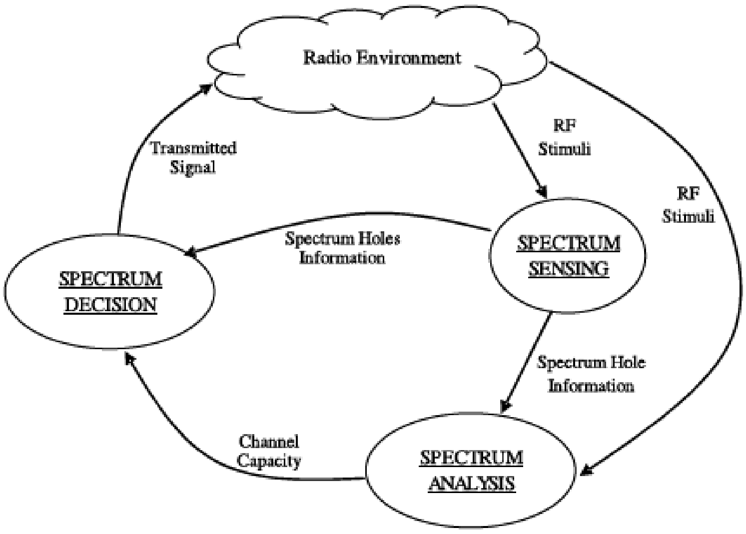

Figure 1.1. Cognitive cycle [5]

1.1. Motivation of the Thesis

Increasing demand on radio frequency bands and low utilization of the licensed frequencies introduces the cognitive radio concept. Achieving simplicity and low computational complexity in design of the cognitive radio devices may decrease cognitive user's awareness of presence of a licensed user. The motivation of this thesis is to increase sensing performance of cognitive devices with a simple sensing algorithm, by using additional location information of licensed users.

1.2. Contribution of the Thesis

In this thesis the average SNR is tried to be increased by using additional location information of the licensed users. There are three different proposed algorithms and an error capacity analysis for the proposed methods. As a result of these algorithms; average SNR, so the sensing performance has been increased. The contributions can be listed as follows:

- Distance information of primary users is used by secondary user to increase the average SNR.

- It is shown that sensing of primary users in a distance based order from the closest to the furthest increases the sensing performance.
- Error capacity of the proposed algorithm in terms of precision of primary user locations is simulated.
- Contribution of knowledge of maximum interference distance is shown. The sensing performance has improved.
- Finally a two user cooperation scheme is proposed to increase average SNR.

1.3. Organization of the Thesis

General information on the cognitive radio structure, spectrum sensing techniques and radio environment map (REM) is introduced in Chapter 2. Proposed methods, problem definition and proposed solutions of the thesis, which is location based spectrum sensing in cognitive radio systems, is introduced in Chapter 3. In Chapter 4, simulations, simulation environment and results are shown. Finally in Chapter 5, conclusion and future work is discussed.

2. COGNITIVE RADIO

Wireless communication market is growing very fast. Parallel to this growth, there is an increasing demand for radio frequencies. Radio frequencies which are and can be used in wireless communications are limited resources. Most of these frequencies are licensed. However it cannot be said that these licensed frequencies are being utilized efficiently in time and space. The increasing demand on the radio frequencies for wireless communications together with the low utilizations of licensed frequencies introduced the 'Cognitive Radio' concept [1, 4]. In Figure 2.1, and Figure 2.2 results of a utilization test is shown. You can see the low utilization of tested frequencies.

Cognitive radio is basically proposing the usage of the licensed spectrum by unlicensed users. By this way the spectrum can be more efficiently used. But the unlicensed users should not interfere with the licensed users. This means the priority of the usage of the spectrum belongs to the licensed user, which is also called the primary user. The unlicensed user is also called the cognitive user or the secondary user [1].

The cognitive radio concept is first introduced by Mitola J. and G. Q. Maguire [6]. A software defined radio is required for cognitive radio. A software defined radio is defined as "Radio in which some or all of the physical layer functions are software defined" in Software Defined Radio (SDR) forum [7]. The definition of cognitive radio is studied by Software Defined Radio (SDR) forum and Institute of Electrical and Electronic Engineers (IEEE) P1900.1 group [7]. Software defined radio is required for cognitive users to use a wide range of frequencies and multiple waveform standards. In order to make multi band, multi mode, multi functional wireless devices, the commonly used hardware based radio devices will require physical modifications, and will cost more. Software Defined Radio is a cheeper and more flexible solution for making this kind of devices. New features and abilities can be easily implemented to software defined radio by software upgrades only. Generalized functional architecture of Software Defined Radio is shown in Figure 2.3.

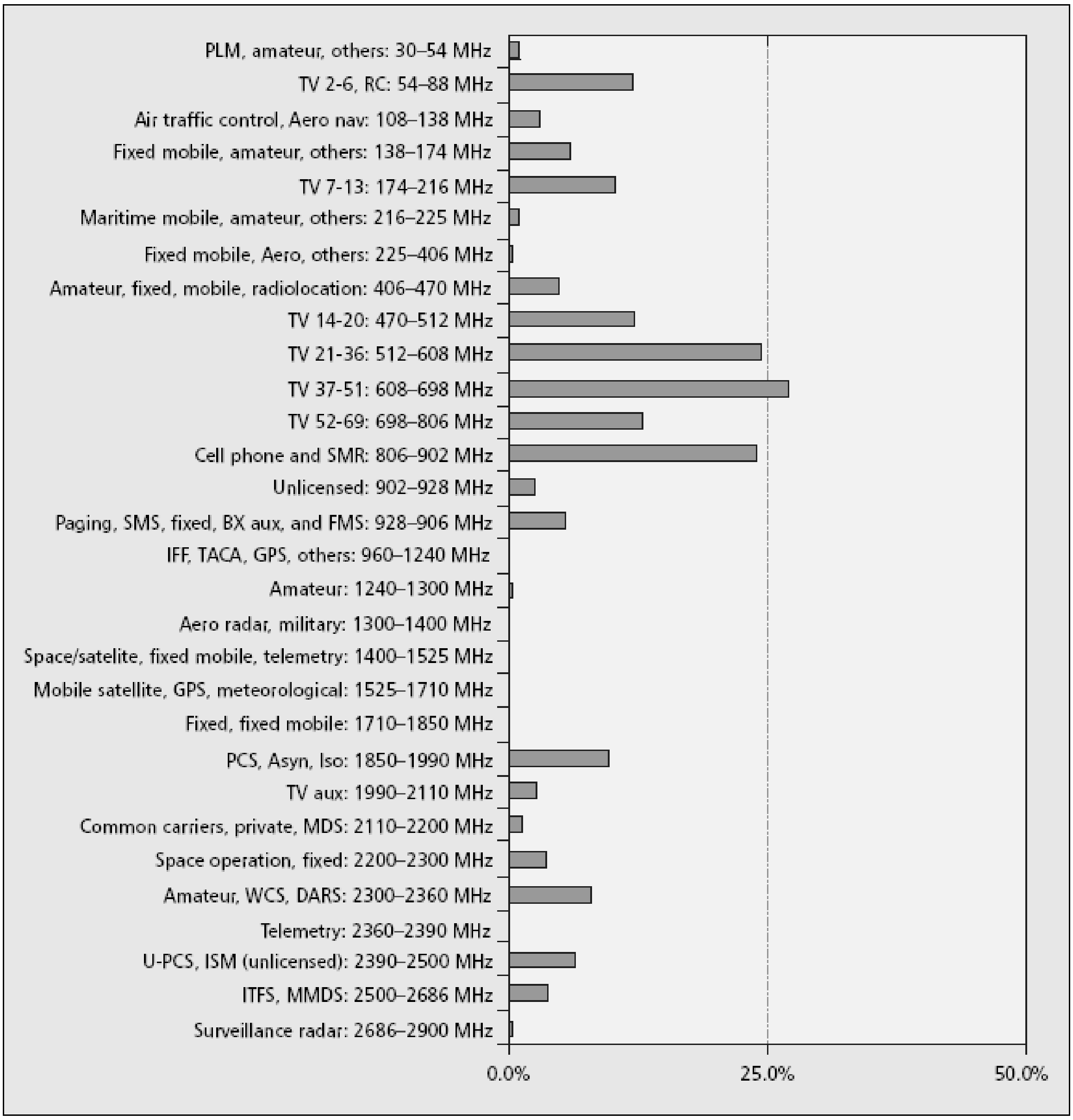

Figure 2.1. Spectrum usage measurements averaged over six locations [1]

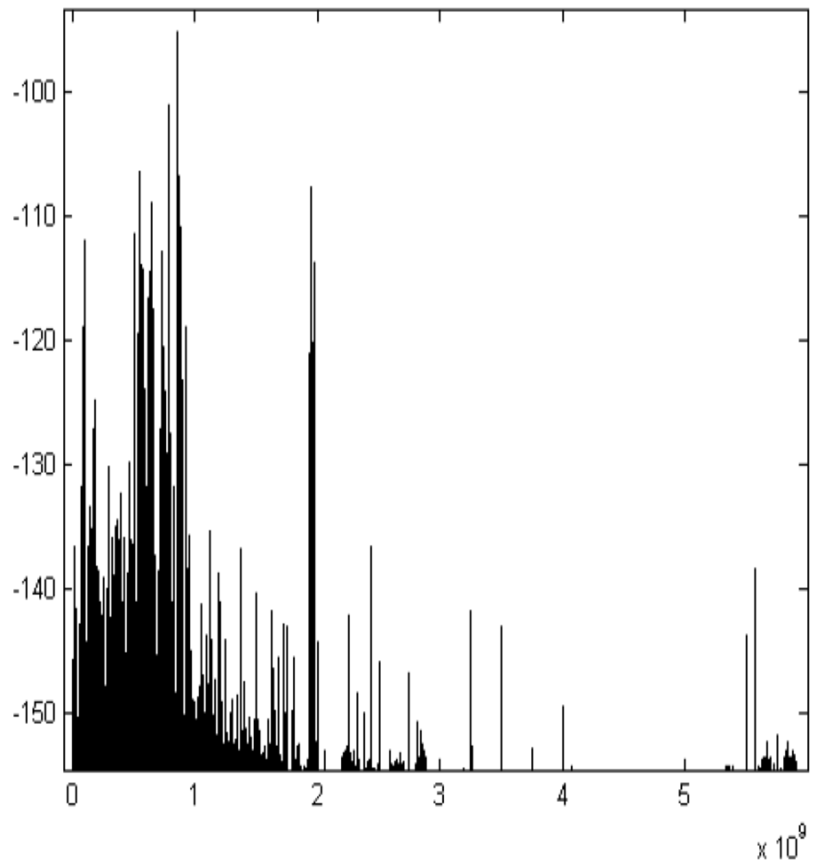

Figure 2.2. Measurement of 0-6 GHz spectrum utilization at BWRC [?]

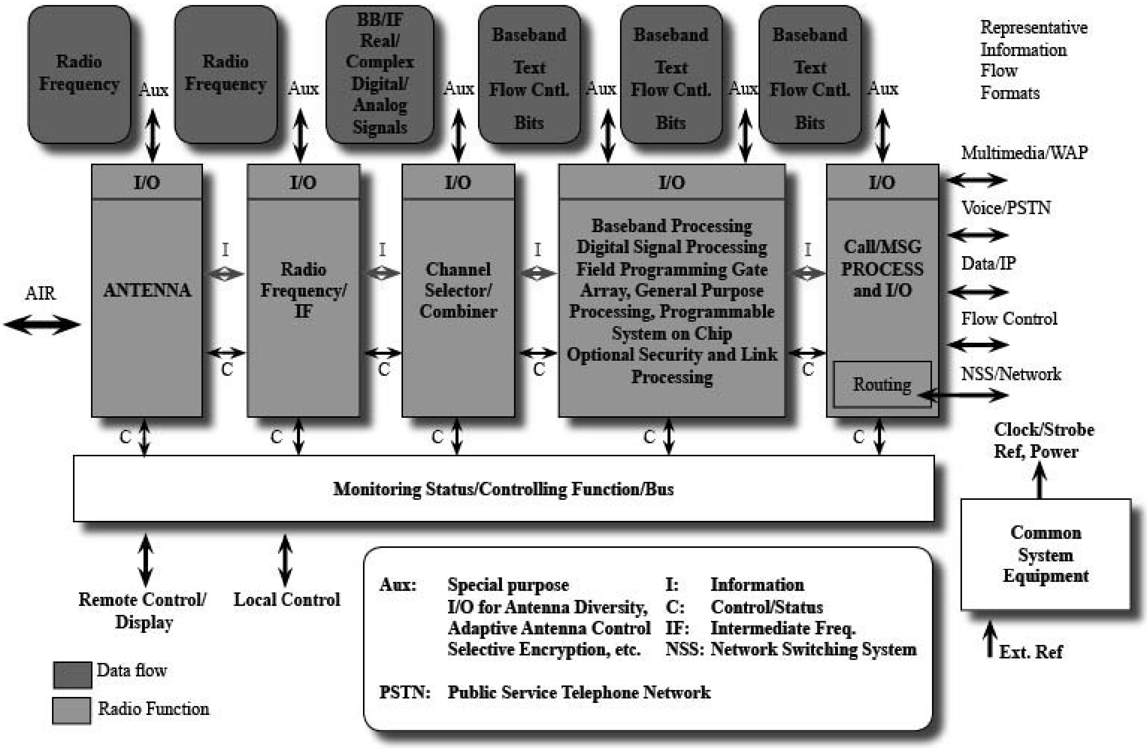

Figure 2.3. Generalized functional architecture of software defined radio [7]

The cognitive users have to detect the presence of the primary user when it is making transmission. There has been some methods introduced for detecting the presence of the primary user or detection of frequencies where primary users are not transmitting, which is called white spaces [1, 4].

- Database Registry: It is introduced to store relevant information of primary users such as primary users' locations, their expected transmission time etc. in a central database.
- Beacon Signals: It is introduced to broadcast information of primary users such as primary users' locations, their expected transmission time etc. in regional beacons
- Spectrum Sensing: Spectrum which is used by the primary users has to be sensed. The secondary users can sense the energy level of the frequency band used, or use a matched filter, if the signal structure is known, or use cyclostationary properties of the primary users to detect their presence and avoid them.

	Infrastructure cost	Legacy compatibility	Transceiver complexity	Positioning	Internet connection	Continuous monitoring	Standardized channel
Database registry	High		Low	X	X		
Beacon signals	High		Low	X			X
Spectrum sensing	Low	X	High			X	

Figure 2.4. Classification of white space identification methods [1]

The properties of white space identification methods are presented in Figure 2.4.

There are a lot of design issues in cognitive radio. The cognitive radio network can be ad hoc, stand alone, or centralized. The spectrum has to be sensed continuously in order to detect the existence of primary user. There are a lot of sensing methods. The users can also try to cooperate in many different ways to increase sensitivity of detection. There are also different spectrum sharing methods. The cognitive radio may also use some foreknown information about the primary users in order to increase sensing performance. This information can be stored in a database which is called as Radio Environment Map (REM). The REM stores the environmental which is like the primary users' location, geographic information, service, regulation and policy information, radio equipment and experience information. The REM concept is introduced in detail in the following chapters.

IEEE 802.22 standardization proposes the usage of cognitive radio in UHF/VHF TV bands; but there are still a lot of open research areas for cognitive radio concept [9, 10, 11, 12].

2.1. Spectrum Sensing in Cognitive Radio

Spectrum sensing is a very important issue in cognitive radio. The secondary users who are using the primary users' licensed spectrum has to minimize the interference to the primary user. To achieve this, they have to minimize the probability of existence of the secondary user in the interference range before they start transmission. Spectrum sensing should be as fast and as accurate as possible. There are a lot of challenges of

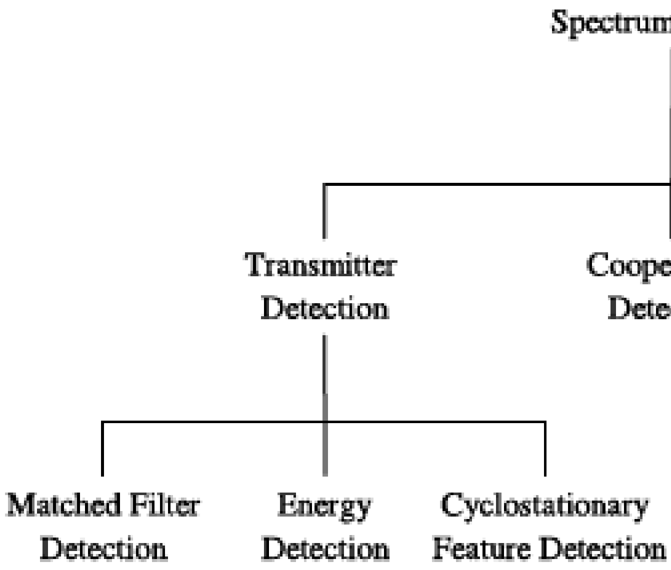

Figure 2.5. Classification of spectrum sensing methods [13]

spectrum sensing and a lot of different techniques and design trade offs between those techniques. We will examine the different sensing methods and sensing challenges in the following sections.

2.1.1. Spectrum Sensing Techniques

There are some basic techniques which are commonly proposed for being used in cognitive radio. One can see the different types of spectrum sensing in Figure 2.5. In the following sections the most commonly proposed techniques are explained. Their advantages and disadvantages are discussed. There can be also some combined methods which joins one or more methods together. With such a method different cases can be handled more quickly and accurately [1].

2.1.1.1. Energy detection. Energy detection is the most commonly proposed technique in cognitive radio. It has low computational complexity and it requires no extra information about the primary user. It has low cost and it is easy to implement. Energy detection measures the energy level in a defined band for a period of time.

As measurement period increases the performance of the energy detector increases. But it is not practical to increase the measurement time too much. The cognitive user can not sense the spectrum and make transmission at the same time. There is a trade of between transmission interval and sensing time. The cognitive radio concept is proposed for utilizing unused spectrum bands, increased sensing time too much will lower the utilization. Also, because the energy detector can not differentiate the resource of the energy, the performance of energy detector decreases at low SNR values. However, energy detection is still the most commonly proposed technique in cognitive radio because of its ease of use [1].

The main aim at spectrum sensing is a two side hypothesis testing. There are two hypothesis. One is H_1, which means there is a primary user transmitting data. the other is H_0 which means there is no primary user transmitting data [14].

$$x(t) = \begin{cases} n(t), & H_0 \\ gs(t) + n(t), & H_1 \end{cases} \tag{2.1}$$

where
$x(t)$ is the received signal by secondary user,
$n(t)$ is the additive white Gaussian noise,
$s(t)$ is the transmitted signal of primary user,
g is the gain of the channel (in this case g includes the path loss effect).

In Figure 2.6 we can see the block diagram of the energy detector [14].The received signal is first passed from a band pass filter and then it is multiplied with itself and integrated, at the end the measured energy level is compared with a threshold and the final decision is made.

The discrete time equivalent of the integrator is summation. The measured energy of the received signal is given as the Equation (2.2).

$$Y = \frac{1}{N}\sum_{k=1}^{N}[x(k) * \overline{x}(k)] \tag{2.2}$$

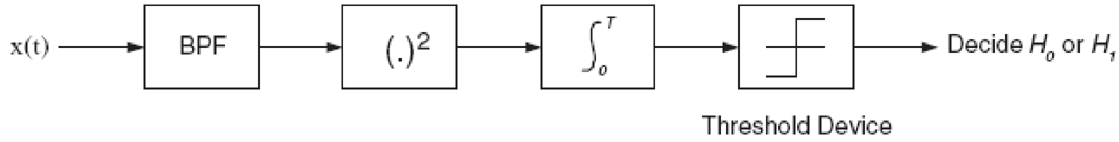

Figure 2.6. Block diagram of energy detection [14].

where,

$x(k)$ is the received signal,

Y is the measured energy of the received signal,

$\overline{x}(k)$ is the complex conjugate of $x(k)$,

N is the number of samples.

The signal is sampled during a time interval T. If the signal which is being sensed has a bandwidth W, the number of samples, N, has to be at greater than or equal to $2WT$ in order to prevent aliasing [15]. Energy detection theory [16] shows that the measured energy, Y, has a chi square distribution in both hypothesis.

$$Y \sim \begin{cases} \chi_N^2, & H_0 \\ \chi_N^2(2\gamma), & H_1 \end{cases} \tag{2.3}$$

where,

Y is the energy of the received signal,

χ_N^2 is the central chi-square distribution with N degrees of freedom,

$\chi_N^2(2\gamma)$ is the non central chi-square distribution with N degrees of freedom,

γ is the signal to noise ratio [14, 16].

N is the number of samples.

In nonfading environment, probability of detection and probability of false alarm are given in Equations (2.4) and (2.5) respectively [14, 16]. The $N/2$ is assumed to be equal to an integer k for simplicity.

$$P_d = P\{Y > \tau | H_1\} = Q_k(\sqrt{2\gamma}, \sqrt{\gamma}) \quad (2.4)$$

$$P_f = P\{Y > \tau | H_0\} = \frac{\Gamma(k, \tau/2)}{\Gamma(k)} \quad (2.5)$$

where,

$\Gamma(k)$ is the complete gamma function,

$\Gamma(k, \tau/2)$ is the incomplete gamma function,

τ is the threshold value and

Q_k is the generalized Marcum Q-function.

Advantages of energy detection are:

- Ease of use
- Low cost
- Simple to implement
- Needlessness of signal information
- Ease of implementation to any kind of signal resource.

Disadvantages of Energy detection are:

- Requires long sensing time
- May not determine the source of the signal (Noise-signal identification is bad under low SNR)

2.1.1.2. Matched filter. The matched filter followed with a threshold test is the optimal detector for cognitive radio. It maximizes the SNR. But it requires the exact information about the signal since the impulse response of the matched filter can be basically defined as Equation (2.6). Matched filter also requires time and carrier synchronization. And all this information has to be available for each of primary user [?].

$$h(t) = s(-t) \tag{2.6}$$

where,
h(t) is the impulse response of the filter and
s(t) is the tracked signal.

It can be very logical to use this kind of a filter if the primary user signal characteristics are known. But matched filter can be used for tracking limited number of primary users. Increased number of primary users will increase the computational complexity. The cost will be high, and complete information of the signal characteristics of primary users may not be available.

Advantages of Matched filter are:

- Maximizes received SNR
- Requires low time to achieve high process gain
- Few number of samples are needed.

Disadvantages of Matched filter are:

- Requires demodulation o primary signal
- Time and carrier synchronization is needed
- A different receiver is needed for each and every primary user which may increase size and complexity.

<u>2.1.1.3. Feature detection.</u> Feature detection is the detection of cognitive user, using some information about the primary user signal such as its modulation type, carrier frequency, bit rate and cyclic prefixes. The computational complexity increases as the

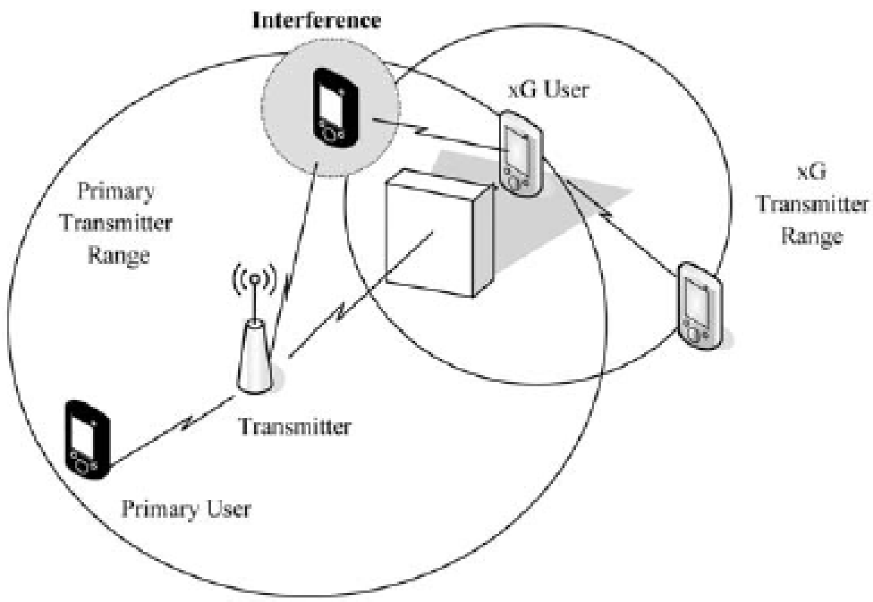

Figure 2.7. Shadowing uncertainty [5].

number of primary users which will be detected increases. Feature detection uses the uniqueness of the spectral correlation properties of different signals [1]. Performance of the feature detector is high in weak primary user signal detection. The sensing time and computational complexity of this method is high, so it is not possible to make real time analysis which is a strong requirement in cognitive radio. But there are techniques which proposes fastened cycle frequency domain feature detection [17].

2.1.2. Spectrum Sensing Challenges

Spectrum sensing has a lot of challenges. First of all, the air interface is full of uncertainties. There are channel uncertainty such as fading and shadowing. The shadowing effect occurs when a cognitive user is unable to detect a primary receiver because of an obstacle between cognitive radio and primary transmitter. This kind of a situation is illustrated in Figure 2.7. There is also noise uncertainty, the type and the power of the noise is not predictable in most of the cases. Some methods such as energy detection is very sensitive to signal to noise ratio.

There is also an aggregate interference problem, which means the interference of

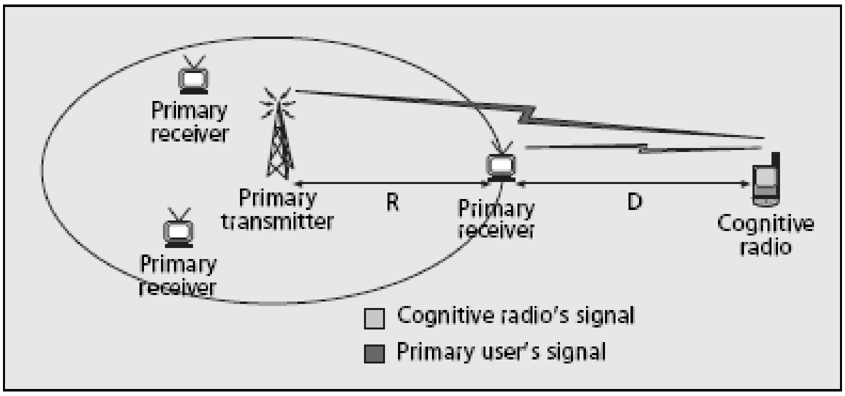

Figure 2.8. Primary receiver detection problem [1]

cognitive users to each others. This problem may be reduced with a secondary base station. A centralized network may schedule the secondary users usage of white spaces.

Sensing periodicity is an individual problem. Since sensing and transmission at the same time is not possible, the secondary user has to do these in separate times. It has to make a schedule, decide how much time it will spend for sensing and how much time it will spend for transmitting. There is a trade off between spectrum utilization and caused interference to primary user.

The main challenge is the primary receiver detection is not possible in most of the cases. The main aim is not to cause interference to the primary receiver. But the thing that we try measure is the primary transmitter. The problem occurs when the primary transmitter is far away such that it can not be detected but the primary receiver is in the middle of primary transmitter and secondary transmitter such that it can hear both transmitted signals. This kind of a situation is illustrated in Figure 2.8 [1, 14]. A different primary receiver scenario is illustrated in Figure 2.9 [5].

2.2. Cooperative Sensing

It is a commonly applied technique to use more than one cognitive user to sense the spectrum. There has been many researches on cooperative sensing and its advantages [**?**, 14, 18, 19, 20]. The main advantage is improved sensitivity. Even when the

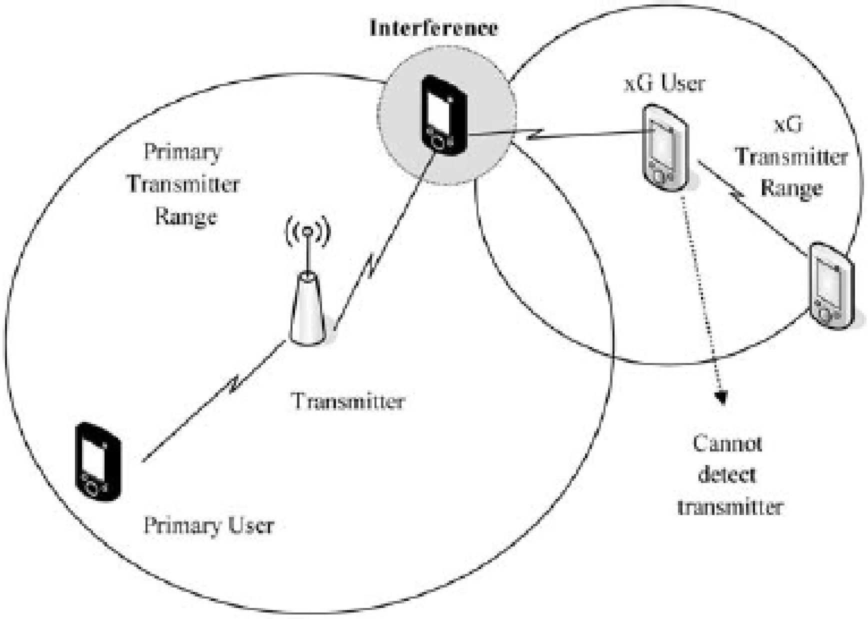

Figure 2.9. Primary receiver detection problem [5]

one bit decisions of the secondary users are collected, the overall detection performance improves. This allows keeping the computational complexity of the individual users low, and receiving a better performance. Another advantage of the cooperation is reducing the fading and shadowing effects. Because the sensing data is collected from more than one user, the possibility of all of the users experiencing the same shadowing and fading effects decreases. The users which do not face shadowing of fading problems reduces these effects and the overall performance increases.

The cooperative sensing has a lot of design issues. The main problem is how the users will cooperate. What kind of information will they send. There is a trade off between local processing overhead and communication overhead. If the cognitive users send too much sensing data the spectrum utilization will lower. Reporting only one bit decisions can be a solution to communication overhead. Where they will send this information is another question. There might be a centralized solution or an ad hoc network solution about it. The combination of these individual information and making a final conclusion is another issue. 'And' logic operator and 'or' logic operator are the most basic ones. The number of users which will cooperate has to be decided

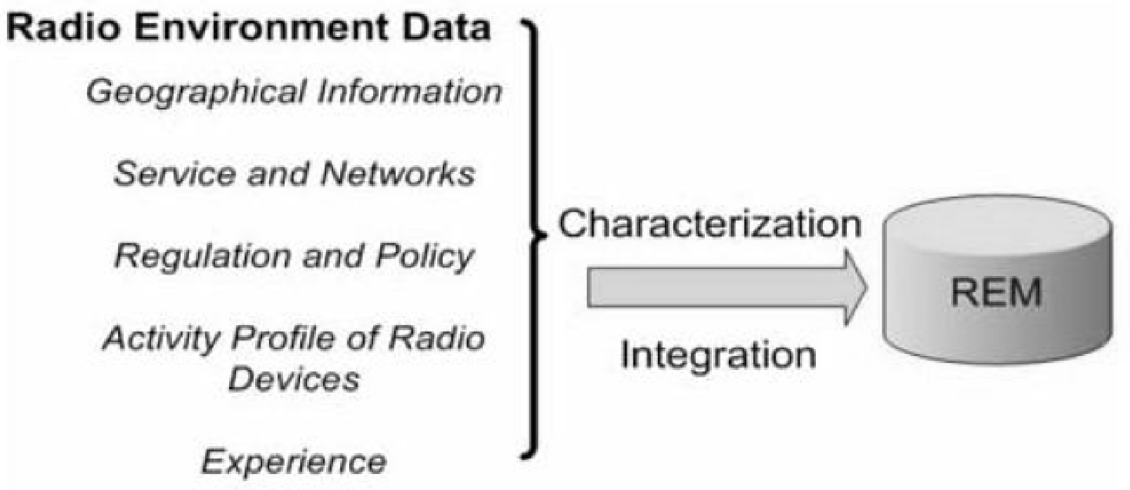

Figure 2.10. Stored information in REM database [21]

too. It will be a good way to decide on it based on fading characteristics [14, 19]. Reactive or proactive sensing should be decided. The secondary users will either sense the environment when it needs to, or will sense the environment any time. Data collection scheme and period is also another design issue.

2.3. Radio Environment Map (REM)

The cognitive radio can achieve the most up to date information about the presence of the primary user by sensing the frequency bands used in the environment. Some information about the geographical properties of the environment such as terrain and buildings; primary user information such as their position, arrival rates, duty ratios, frequencies, modulation types and signal properties, services and regulation, statistical information about the behavior of the primary users and past experiences of the other secondary users can do a great help to the cognitive user. The Radio Environment Map is the general idea for a database which stores this kind of information. Figure 2.10 and Figure 2.11 shows the information stored in REM database its structure [21, 22].

The main aim of REM database is to provide necessary information to secondary users to increase their performance. If the secondary users know some information about the primary user or the environment or the past experiences of the other sec-

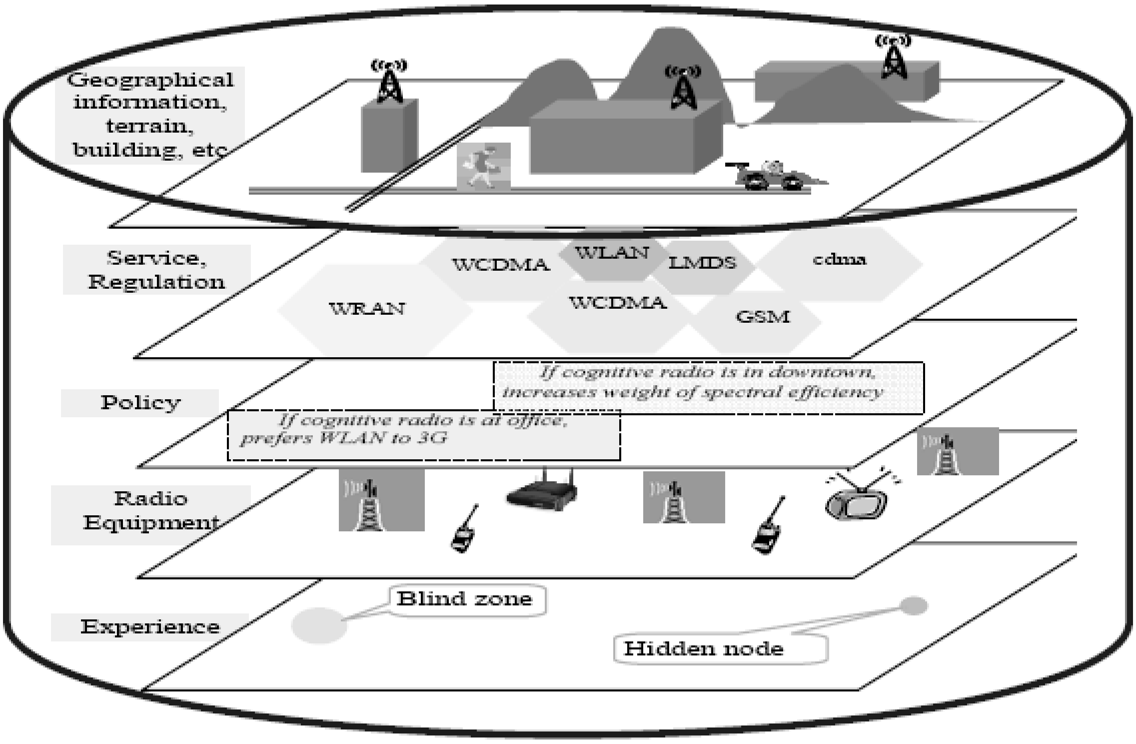

Figure 2.11. REM database structure [22]

ondary users, the overall performance will be enhanced. There are two proposes of the radio environment map. The first one is making use of the stored information in this database. The secondary users can use this kind of an information for network initialization, starts sensing by the potentially empty channels. From historical REM information the cognitive base station can define spectrum usage schedules of the primary and secondary users and make arrangements about the distribution of the spectrum. The cognitive user transmission power control parameters can be extracted from REM information. One of the most important purposes is the awareness and protection from primary users via increasing sensing performance. Fast adaptation and fast finding of an empty channel can be performed. Radio resources management and optimization via increasing network throughput and spectrum utilization can be accomplished. primary user emulation effects can be prevented, cognitive radio performances can also be evaluated for feature use [23].

The second purpose of the Radio Environment Map is the collection and recording of the information. Some database information can be obtained from the primary user systems such as primary user locations, frequencies, modulation types and signal properties, services and regulations. Some information is environmental such as terrain information and geographical surface information. Some information such as spectrum usage patterns, arrival rates, duty ratios and similar statistical information about the behavior of the primary users can be obtained by experiences of secondary users and learning algorithms. This part of REM is beyond the scope of this thesis [23].

3. LOCATION BASED SPECTRUM SENSING IN COGNITIVE RADIO SYSTEMS

3.1. Problem Definition

One of the main purposes of the cognitive radio is not to disturb the primary user. To achieve this aim the cognitive user has to sense the spectrum constantly and reliably. The sensing should be reliable for protection of primary user from interference.

Another purpose of cognitive radio is to increase its transmitted data volume. There is a trade off between sensing time overhead and transmission time. The less time a cognitive user spends to find an idle channel, the more quickly it begins to transmit data. So, finding an empty channel as quickly as possible, and not giving false alarms of primary user becomes an important issue for utilizing radio channels.

The aim of this thesis is to achieve these two purposes together. With help of Radio Environment Map (REM) concept, location information about primary users the can also be used to achieve higher performance. As the SNR of the primary signal increases, the sensing performance will increase. You can see the SNR versus bit error rate (BER) performances on the Figure 3.1 [24, 25]. The bit error rate decreases, so the sensing performance increases, as the SNR of the signal increases in different accelerations in different modulations. The main question is in which sequence cognitive users have to start sensing the primary users in order to increase the average SNR, so increase the sensing performance and transmitted data volume.

3.2. Proposed Solutions

In the proposed solutions, spectrum energy detection algorithm is selected because of its ease of implementation, low cost and low computational complexity. SU uses energy detection algorithm for each usable PU frequency band. Also the location information of primary users are assumed to be kept in REM database.

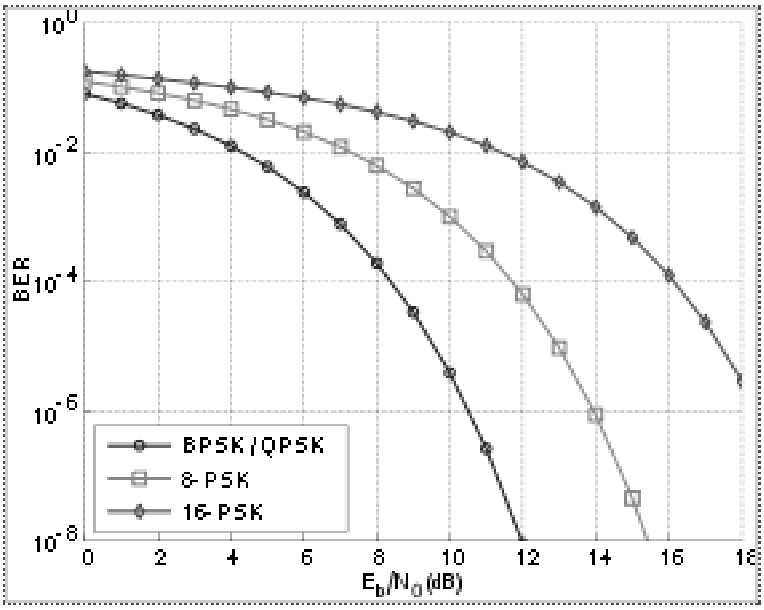

Figure 3.1. SNR versus bit error rate (BER) performances [25]

The cognitive user may not be configured to use all frequencies. The secondary users have to sense the primary transmitters whose frequencies it can use, and should not use these frequencies if they are being used by a primary user in their interference area. Sensing all the usable frequencies all the time, which is proactive sensing, is unnecessary and causes a lot of computation and this will shorten the lifetime of the battery of the cognitive device. Reactive sensing which is sensing for an empty channel when it is needed will be used in this work.

The cognitive user may be capable of transmitting at a large number of frequencies, and the question about necessity of sensing all frequencies arises here. In this thesis it is decided that the cognitive user shall stop searching when it finds an empty channel, which is a straightforward solution for decreasing sensing time, and utilization of time and frequency usage.

The probability of detection of a primary user should be as high as possible in order not to disturb the primary user. The false alarm rate should be as small as possible to find an idle channel and to increase secondary user transmitted data volume. The overall sensing performances can be measured with Receiver Operating Characteristics (ROC) curve. ROC curves plots probability of detection versus probability of false alarm. The ROC curves are used in this thesis to measure the performance of proposed algorithms.

The inverse relation between SNR and primary user secondary user distances and direct proportional relations between SNR and sensing performance is used in the basis of the proposed solutions. Detailed descriptions of different proposed methods and their performance evaluations are listed in the following sections.

3.2.1. Primary User Distances Based Sensing

Considering the fluctuations in the transmitted primary user signal, fading effects should be considered for those signals. Observations are made for long term and the average signal power is calculated. So, the large scale fading effect should be considered. Path loss that is mentioned in this work is average path loss because of long term observations [26, 27].

It is known that when the distance between the sensor and the sensed signal source increases, the average path loss will increase and hence the calculated average signal power will decrease [27]. There is an inverse proportion between the average signal to noise ratio (SNR) and distance of the signal source. Path loss at a distance d is given in the following formula, where d is always greater than or equal to $d0$.

$$PL_d\,(dB) = PL_{d0}\,(dB) + 10nlog_{10}\left[\frac{d}{d0}\right] \tag{3.1}$$

where;
$PL_d(dB)$ is the path loss at a distance d in decibels,
$d0$ is the reference distance at which the path loss is known,
n is the path loss exponent which changes from environment to environment as shown in Table 3.1.

$d0$, which is the reference distance is chosen to be close to the resource, such that

Table 3.1. Path loss exponent for different environments

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

the path loss at point $d0$ is assumed to be 0. So the formula 3.1 turns into:

$$PL_d(dB) = 10nlog_{10}\left[\frac{d}{d0}\right] \tag{3.2}$$

$$PL_d = \left[\frac{d}{d0}\right]^n \tag{3.3}$$

$$PR_d = PT \Big/ \left[\frac{d}{d0}\right]^n \tag{3.4}$$

where;

PT is the power transmitted,

PR_d is the power received at point d.

While additive white Gaussian noise power is assumed to be the same for the environment, and the signal power of the primary users are assumed to be the same, the signal to noise ratio (SNR) will be lower as the distance between the cognitive user and the sensed primary user increases. If there are m primary users to be sensed, which are listed according to their distances without loss of generality $d_1 \leq d_2 \leq ... \leq d_m$, the SNR of them will be in the $SNR_1 \geq SNR_2 \geq ... \geq SNR_m$ order. This order is based on neglecting the effects of shadowing. In this work, shadowing effects are only considered while choosing the path loss component. Independent shadowing effects of each primary user is not simulated. Of course, primary users' signals with different shadowing effects will change the order of the SNR levels and lower the performance of the proposed method. Another assumption is about the probability of availability of each channel. The probability of the availability of each channel is assumed to be the same. So, the expected number of channels to be sensed until the cognitive user finds an empty channel is fixed. The average SNR will be the average of the SNR's of the primary users which are chosen to be sensed until an empty channel is found. In order to maximize the expected average SNR, the secondary user is proposed to start sensing from the primary signal with highest SNR, which is the closest one. When the locations of the primary users and the secondary user are known by REM, the distances can be calculated and the cognitive user can start sensing from the closest one. If the expected value of average SNR is maximized, the overall sensing performance is enhanced. The receiver operating characteristics curve will be improved.

In order to make the sensing method more realistic, if the cognitive user finds an empty channel and tunes on it, the next time it senses, it starts sensing from the previously found channel no matter what its distance is. If that channel is not empty, than it starts sensing from the closest primary user. The pseudo code for proposed algorithm is given in Table 3.2. The simulation results are presented in the Chapter 4.

3.2.2. Erroneous Primary User Distance Based Sensing

The distance information until this section is assumed to be known and exact. But this is not a realistic situation. If primary user locations are not in the exact positions which we know but has some errors on it, how much the performance is decreased. This section offers to measure the sensitivity of the proposed method to the distance errors. The less the sensitivity, the more realistic environments the proposed method will work.

Table 3.2. Pseudo code for distance based sensing

```
IF an empty channel was found in the previous sensing
    Sense that previous channel.
    IF previously empty channel is still empty
        Go on using that channel.
    ELSE
        Start sensing from the closest PU until you find an empty channel.
    END IF
ELSE
    Start sensing from the closest PU until you find an empty channel.
END IF
```

3.2.3. Maximum interference Distance Based Sensing

There is a maximum distance that a cognitive radio can transmit data, which can be shown as D in Figure 2.8. And there is also a maximum distance that a primary user can transmit data, which can be shown as R in Figure 2.8. The maximum primary user secondary user distance, which can be shown as $D + R$ in Figure 2.8, is called the interference distance (ID). Any primary transmitter which is away from the interference distance cannot be interfered.

In this proposed method, in addition to the location information of the primary users, the maximum interference distance is also assumed to be known by REM. The cognitive user can use the frequency channels of the primary users which are outside that range without sensing. If there is no primary users outside the maximum interference range, than the cognitive user has to sense the frequency channels beginning from the previously used PU channel and than the closest PUs. As it was in the previous algorithm, if there is no PU outside the interference range, the cognitive user will first sense the previously used channel, if it is not empty, it will start sensing from the closest PU channel. The pseudo code of the algorithm is given in Table 3.3.

Table 3.3. Pseudo code for maximum interference distance based sensing

```
IF There is a PU outside ID range
    Use that PU's channel.
ELSE
    IF An empty channel was found in the previous sensing
        Sense that previous channel.
        IF previously empty channel is still empty.
            Go on using that channel.
        ELSE
            Start sensing from the closest PU until you find an empty channel.
        END IF
    ELSE
        Start sensing from the closest PU until you find an empty channel.
    END IF
END IF
```

3.2.4. Primary User Distance Based Two User Cooperative Sensing

The proposed method is designed for one cognitive user case. If there are two cognitive users, let us say user i and user j, another cooperative sensing method has to be offered. This section proposes a technique for cooperation and sensing of two cognitive users. Each cognitive user shall start sensing individually from the closest primary user to itself and continues with the next closest. if the next closest primary user to cognitive user i is closer to the cognitive user j, the cognitive user i does not sense that frequency channel and stops sensing. The sensing procedure goes on until one of them finds an available channel. Here it is assumed that the cognitive users will share one frequency channel and one frequency channel is enough for the transmissions of both secondary users. Pseudo code of the proposed method is shown in Table 3.4 and Table 3.5.

Table 3.4. Pseudo code for distance based cooperative sensing:part one

```
IF an empty channel was found in the previous sensing
    The corresponding SU senses the same channel.
    IF The channel is empty
        They use that channel.
    ELSE
        WHILE No empty Channel Found,
        and there are unmeasured PUs
            Each SU measures the next closest PU distance.
            IF the next closest PU to SU_i, is closer to SU_j
            and next closest PU to SU_j, is closer to SU_i
                They both stop sensing.
            ELSE IF the next closest PU to SU_j, is closer to SU_i
                SU_j stops sensing,
                SU_i senses next closest PU.
            ELSE IF the next closest PU to SU_i, is closer to SU_j
                SU_i stops sensing,
                SU_j senses next closest PU.
            ELSE
                Each SU senses the next closest PU.
            END IF
        END WHILE
    END IF
```

Table 3.5. Pseudo code for distance based cooperative sensing:part two

ELSE IF an empty channel was not found in the previous sensing
    WHILE No empty Channel Found,
    and there are unmeasured PUs
        Each SU measures the next closest PU distance.
        IF the next closest PU to SU_i, is closer to SU_j,
        and next closest PU to SU_j, is closer to SU_i
            They both stop sensing.
        ELSE IF the next closest PU to SU_j, is closer to SU_i
            SU_j stops sensing,
            SU_i senses next closest PU until it finds an empty channel.
        ELSE IF the next closest PU to SU_i, is closer to SU_j
            SU_i stops sensing,
            SU_j senses next closest PU until it finds an empty channel.
        ELSE
            Each SU senses the next closest PU until they find an empty channel.
        END IF
    END WHILE
END IF

4. SIMULATION RESULTS

In this chapter, the simulation environment, and the simulation results are presented. The sensing performance of the proposed algorithms are measured with Receiver Operation Characteristics (ROC) curves. The resulting curves and the simulation results are discussed.

4.1. Simulation Environment

The simulation code is written in Matlab. Simulation environment is a square area with $1km \times 2.4km$ size. There is one or two secondary users and 15 primary users in the area [28]. The secondary users are distributed in the simulation area randomly at each different simulation. Each primary user uses a different frequency for transmission.

The locations, and the used frequency information of primary users are known by REM. The secondary user's position information is also known by REM. The REM calculates the distances and sends these distances and the related frequencies, which are used by the primary users at these distances, to the cognitive user(s). The cognitive user(s) will start sensing beginning from the closest primary user. The reference distance which is shown as $d0$ in Equation (3.1), is assumed to be $10m$, and the path loss at this distance is assumed to be zero [27]. A list of common parameters is listed in the Table 4.1. The ROC curves are used for performance evaluation of sensing. Sensed energy is measured in dB; energy detection threshold is changed from $-6dB$ to $-2.5dB$ and ROC curves are created accordingly.

For different proposed techniques, there are some modification of some parameters, which will be explained in detail in the following sections.

Table 4.1. Simulation parameters

Parameter	Value
Field size	1km x 2.4km square
Number of primary users	15
d0	10m
Fading	large scale fading
Noise	AWGN

4.2. Simulation Results

The results are examined under four different categories. The first one is when only the primary user distances are known, the next one is error tolerance of the method. The simulation results when when maximum interference distance is also known and a simple two user cooperation algorithm are also explained in the following sections.

4.2.1. Primary User Distances Based Sensing

This is the basic algorithm of all the following sections. There is one cognitive user and 15 primary users distributed randomly in the simulation area, each of which uses a different frequency band. The cognitive user only knows the distances and the spectrum bands of the primary users. The simulation environment is shown in Figure 4.1. The cognitive user is assumed to be moving on a straight line along the simulation area with a $20m/sec$ speed which is shown with a line in Figure 4.2.

In this algorithm the secondary user starts sensing from the closest PU to the furthest and stops sensing when an empty channel is found.

The first simulation is made where the SNR within $d0$ is assumed to be $10dB$ and decreasing with the distance. The environment is free space which means path loss

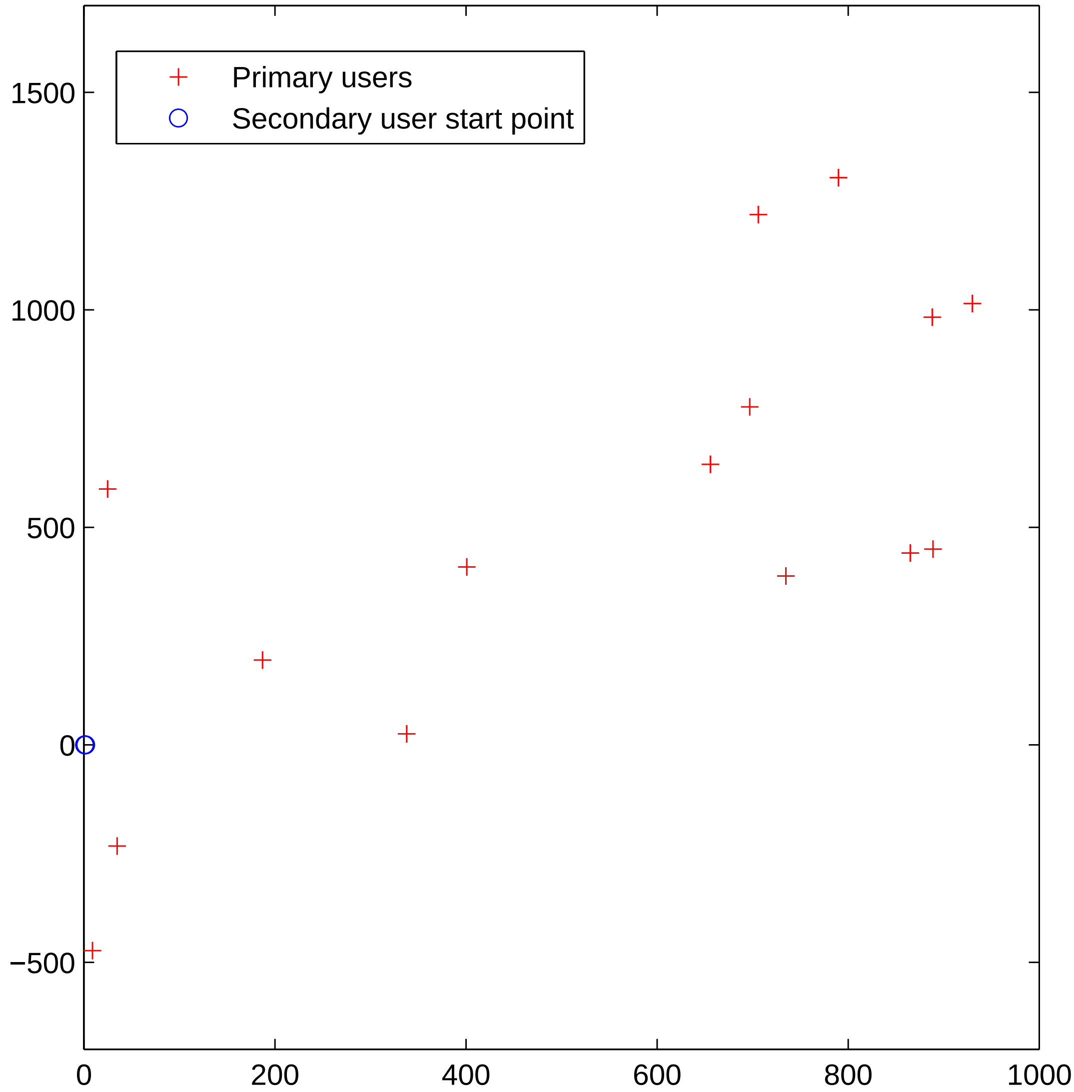

Figure 4.1. An example for simulation area

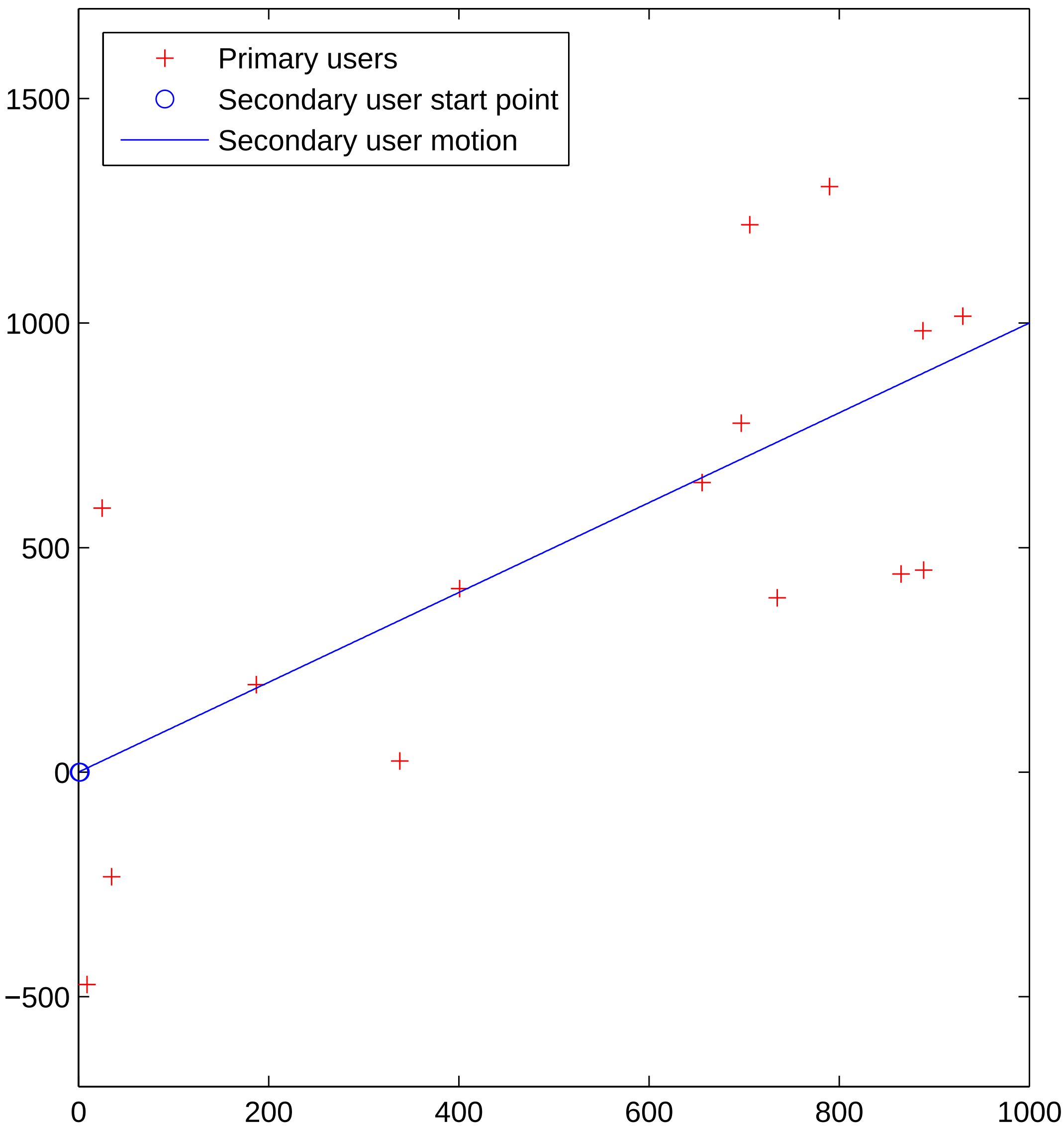

Figure 4.2. An example for simulation area with SU moving

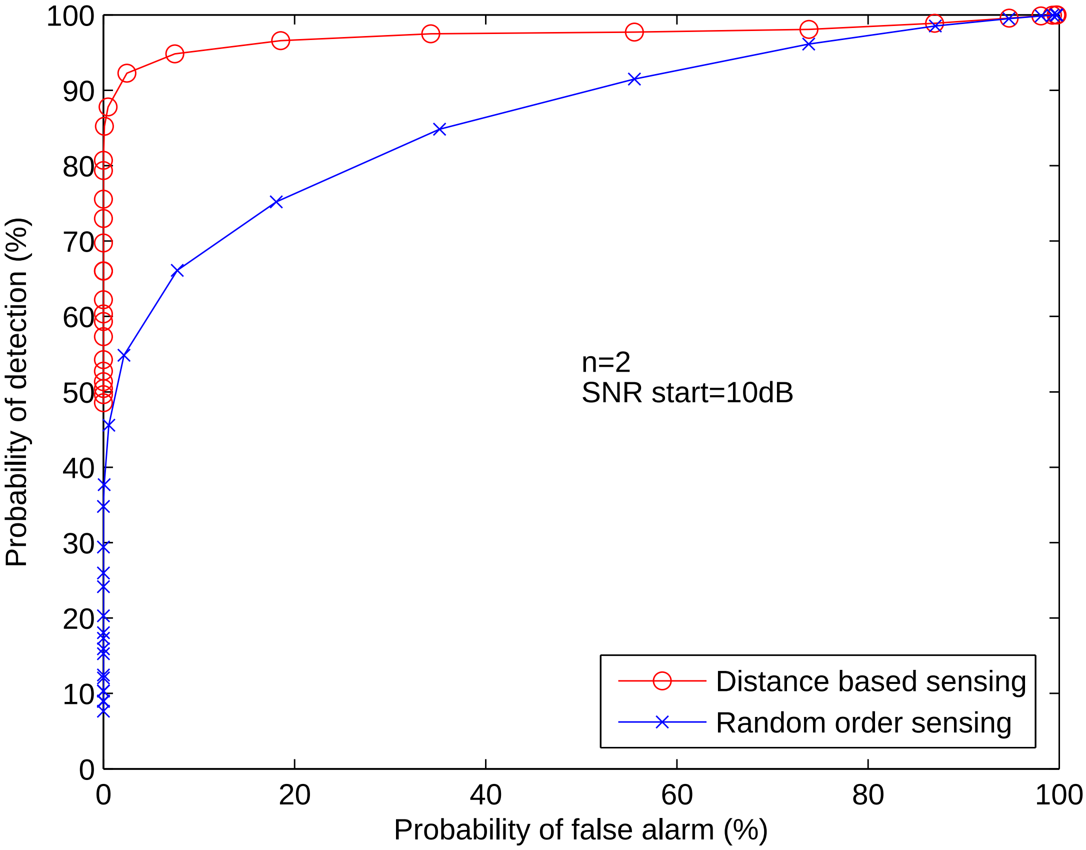

Figure 4.3. ROC curve result for free space environment SNR start=10dB

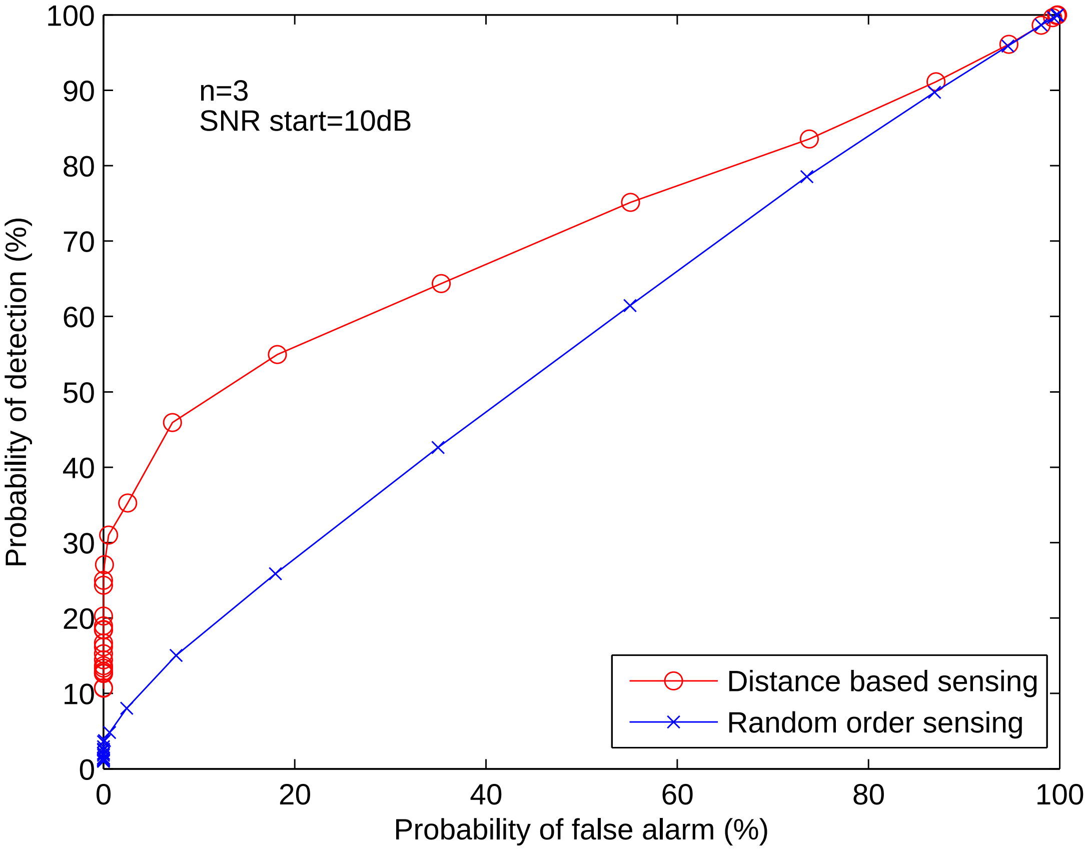

Figure 4.4. ROC curve result for urban environment SNR start=10dB

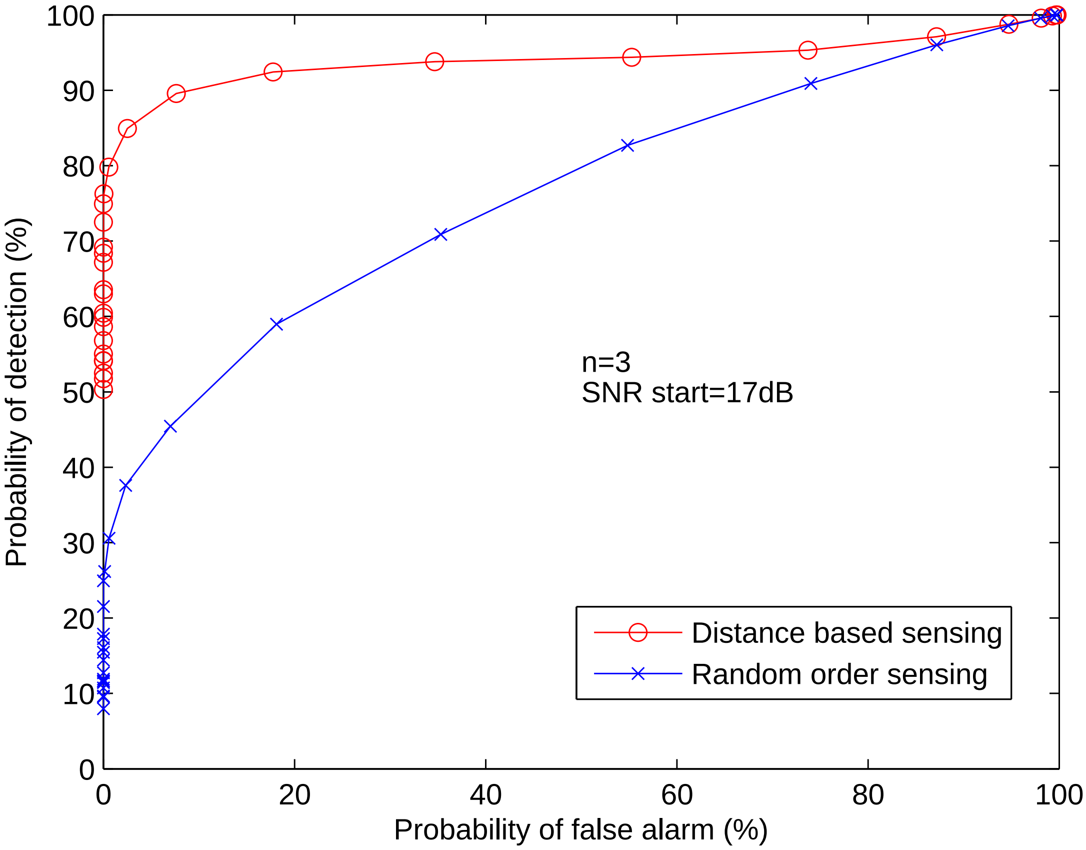

Figure 4.5. ROC curve result for urban environment SNR start=17dB

component n is two. The simulation result of the proposed method is compared with a random order method. In the random order method, the primary users are sensed in a random sequence, and the cognitive user stops sensing when it finds an empty channel. The results are shown in Figure 4.3. As can be seen from the ROC curve, the PU location based sensing gives better results and increases the sensing performance.

Another simulation is done for urban area environments, which means the path loss component n is three. SNR within the $d0$ is assumed to be $10dB$ and decreasing with the distance. The results are shown in Figure 4.4. Here also it can be seen that the PU location based sensing has better performance. But because the environment is urban area, the performance of PU location based sensing and random order sensing both decreases compared to free space. The same simulation (with $n = 3$) is also made with increased PU signal power (SNR within the $d0$ is assumed to be $17dB$ and decreasing with the distance). The results are shown on Figure 4.5. It is clear that distance based sensing improves the performance.

4.2.2. Erroneous Primary User Distance Based Sensing

The location information, hence the primary user-secondary user distance information is assumed to be exact in the previous proposed solution. But in reality this is not the situation. The location information may have some error. The effects of the erroneous location information will be discussed in this section. The performance of the proposed method under some erroneous primary user information is compared with the random order sensing method. $100m$ error on primary user locations is illustrated in Figure 4.6 on a simulation area example.

In this section, in order to understand the performance of the proposed method under erroneous data, the maximum error is considered. That means in order to understand the $100m$ error on the performance, the distance between primary user and secondary user is manipulated $\pm 100m$, not in a $[0\ 100m]$ range. Each PU-SU distance is manipulated individually.

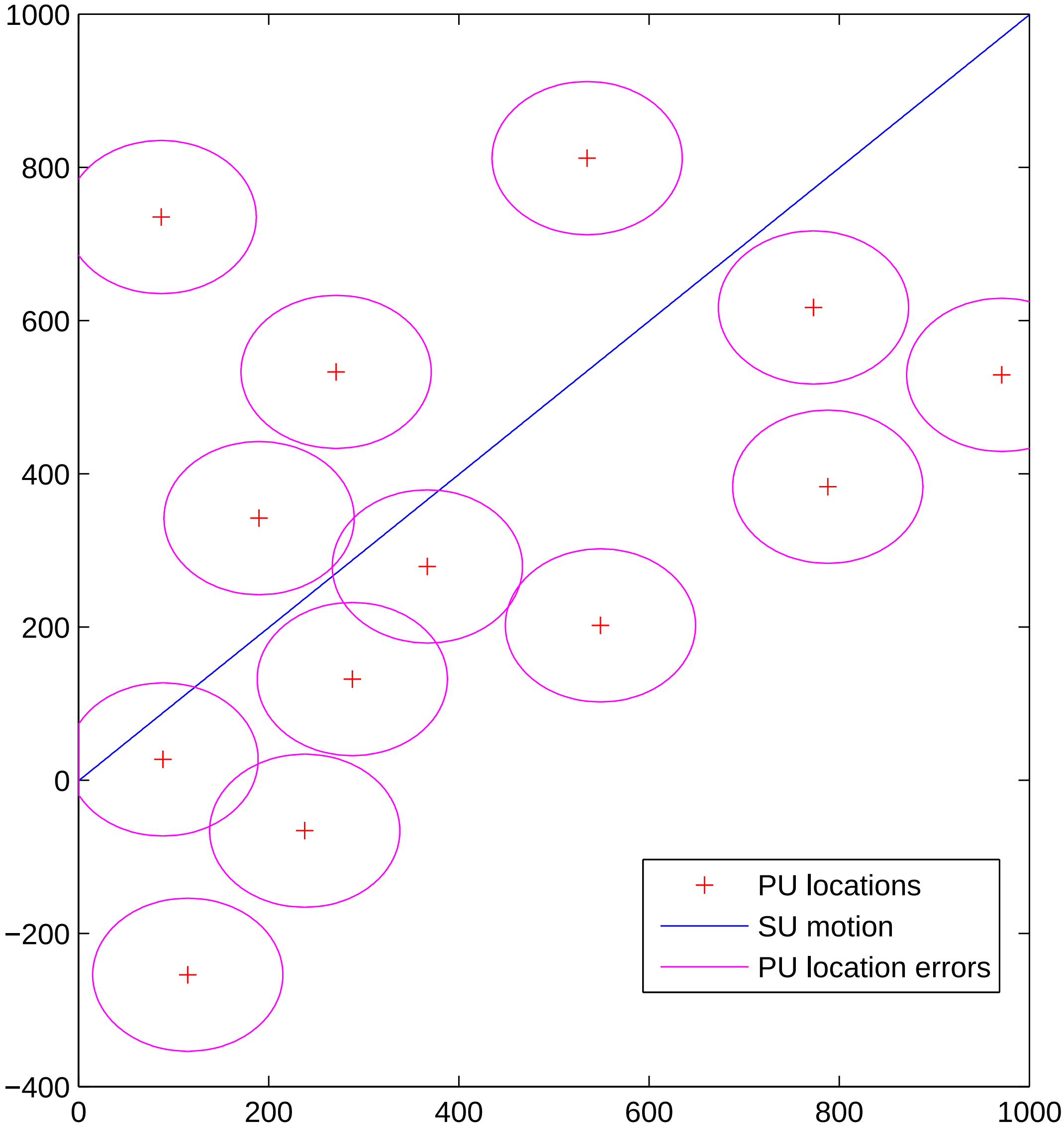

Figure 4.6. Environment example for 100m error on location information

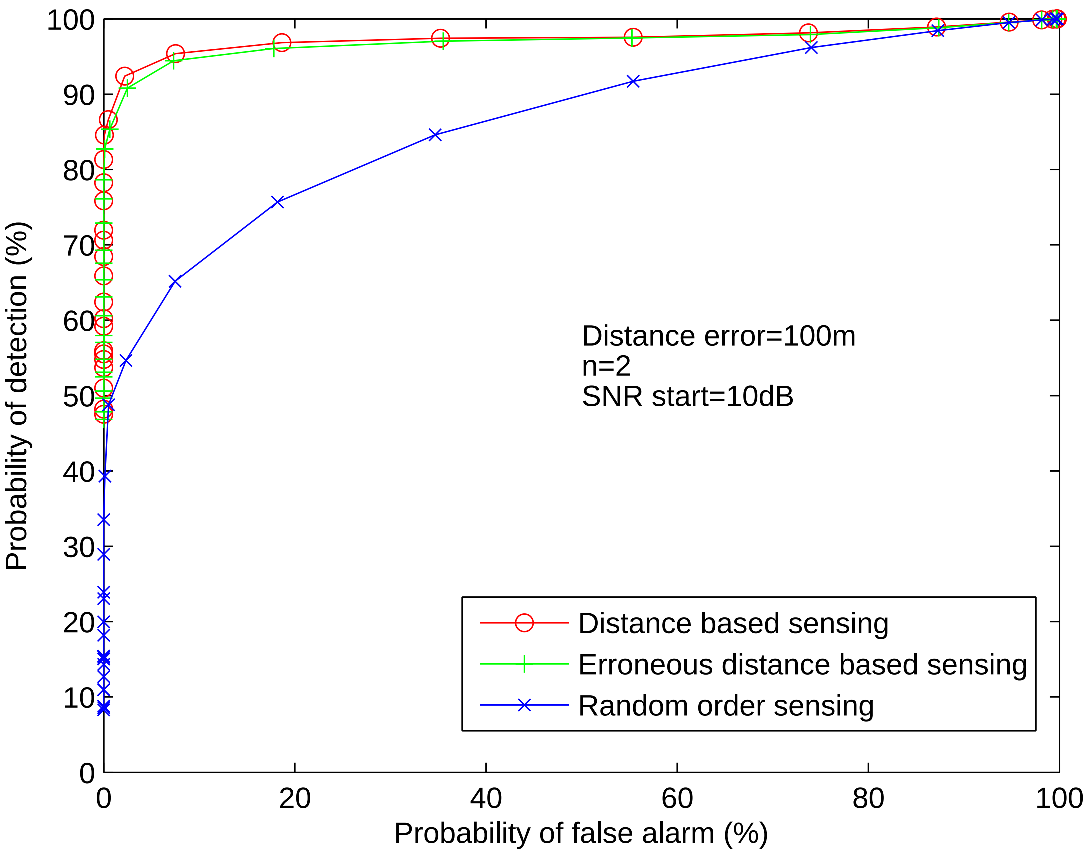

Figure 4.7. ROC curve result for free space environment for 100m error on location information

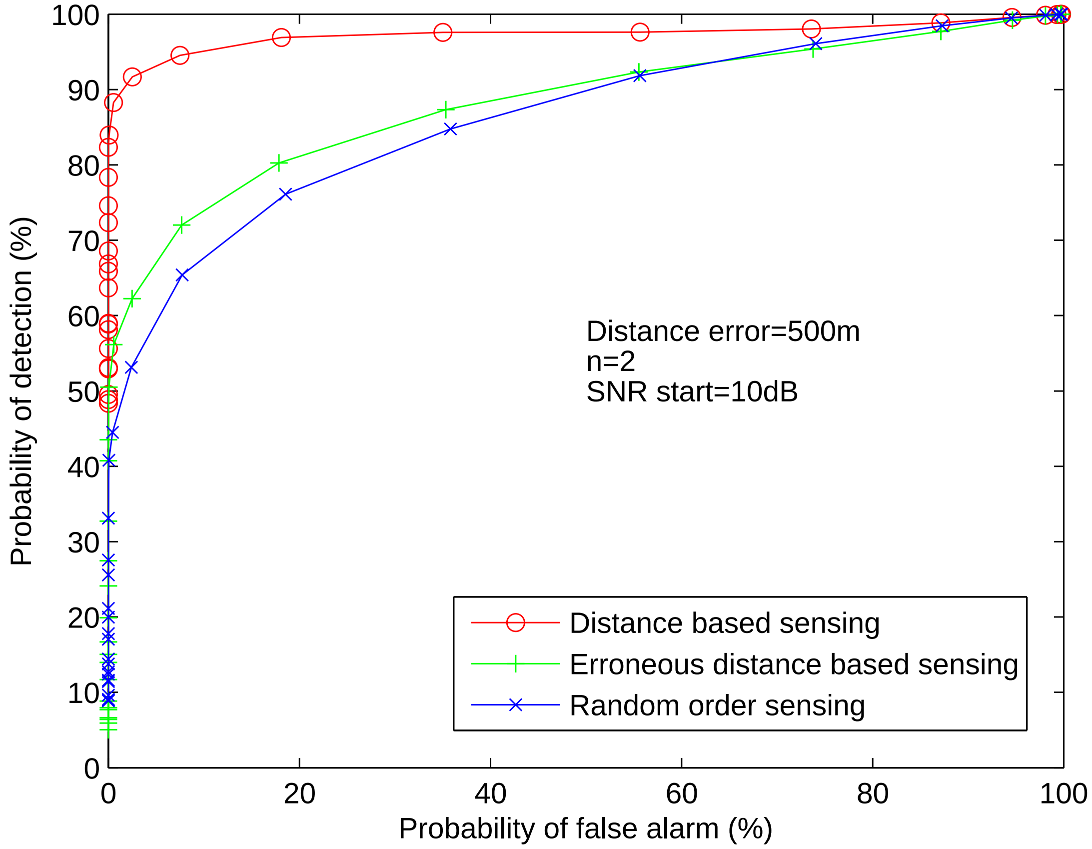

Figure 4.8. ROC curve result for free space environment for 500m error on location information

The ROC curve results are shown on Figure 4.7 for a $\pm 100m$ error on PU-SU distances. It is seen that $100m$ error is still as good as the proposed method. The proposed method is related to the PU-SU distances. The SU senses the primary users from closest to the furthest. So the exact distances are not so important. The important thing is the list of PUs from closest to the furthest which can be effected by the PU distance errors and by the distance between the PUs. As it can be seen from the Figure 4.6 $100m$ does not change the order of the PUs in our simulations much when we list them from the closest to the furthest. The average distance between primary and secondary users are $625m$ in average for this simulation environment. $100m$ is 16 per cent change referred to the average distance between the PUs. This is the reason of that little change on the ROC curve.

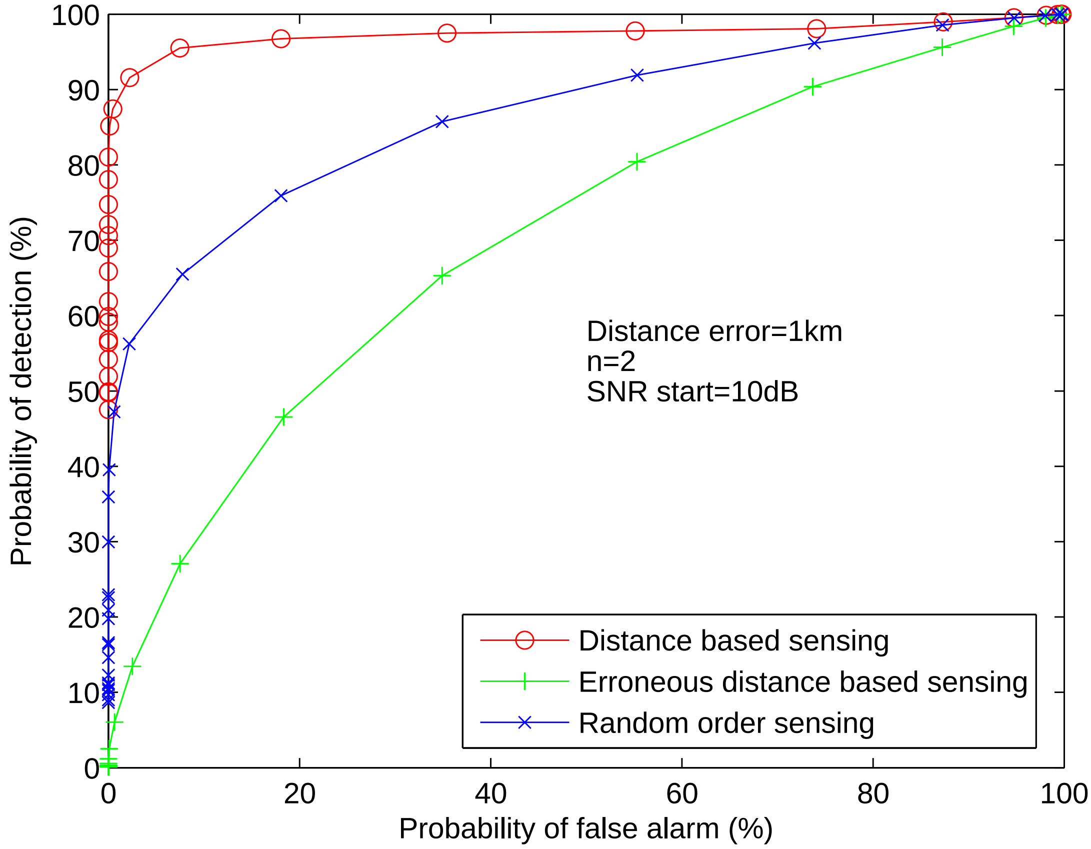

Figure 4.9. ROC curve result for free space environment for 1km error on location information

If the PU's were closer to each other or the error on the PU locations were larger as it is on Figures 4.8 and 4.9, the performance will be lowered. In Figure 4.8, the distance error is $500m$ which is 80 per cent of the average distance between the PUs. The proposed technique gives similar results with the random order method, so it seems to be the limit error for this technique. As can be seen from Figure 4.9, greater error than 80 per cent of the distances between PUs will give a worse result than the random order selection.

4.2.3. Maximum Interference Distance Based Sensing

In this method it is assumed that the maximum interference distance is assumed to be known, and if there is a PU outside that IR range then it can use this PU's

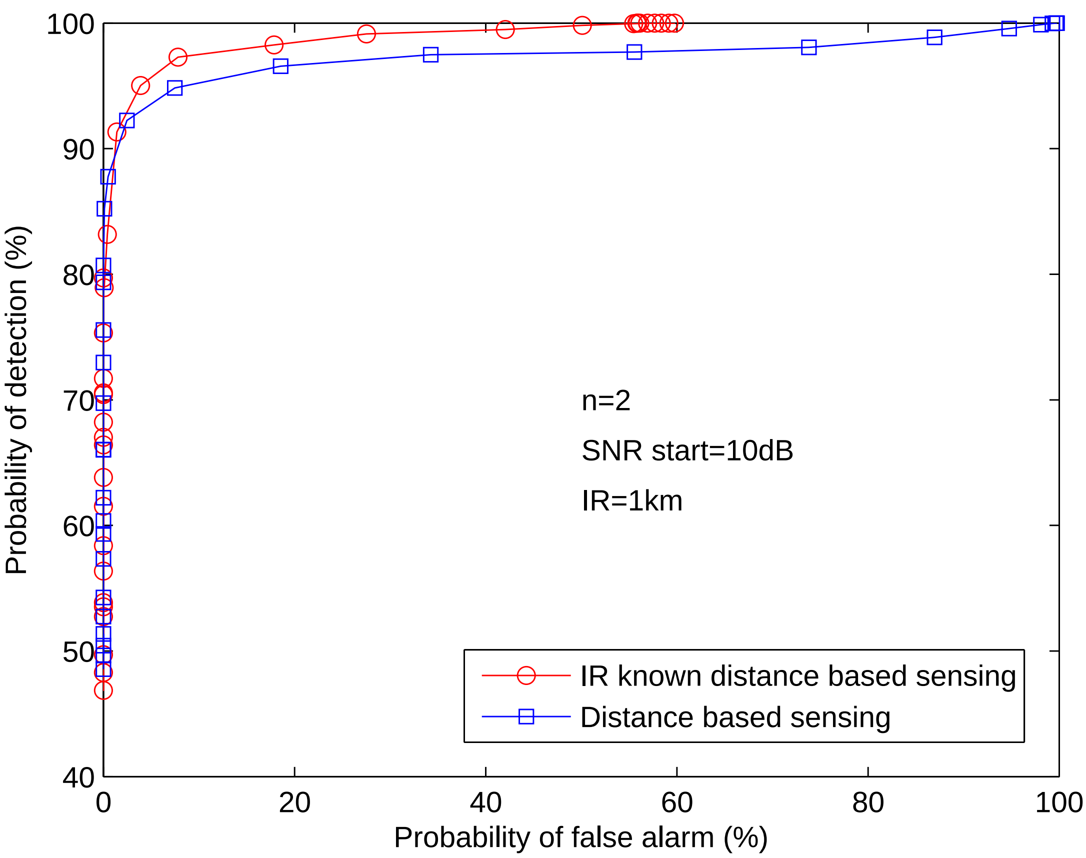

Figure 4.10. ROC curve result for free space environment for IR known and IR not known simulations

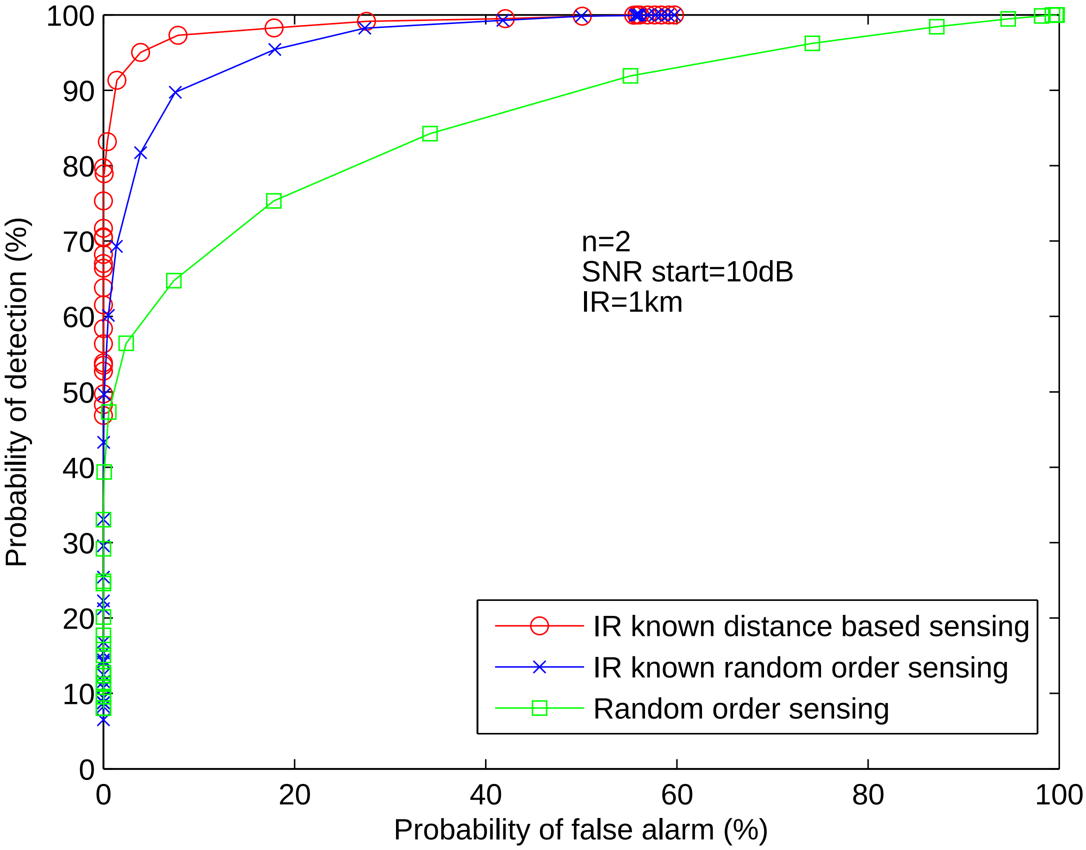

Figure 4.11. ROC curve result for free space environment for IR 1 km

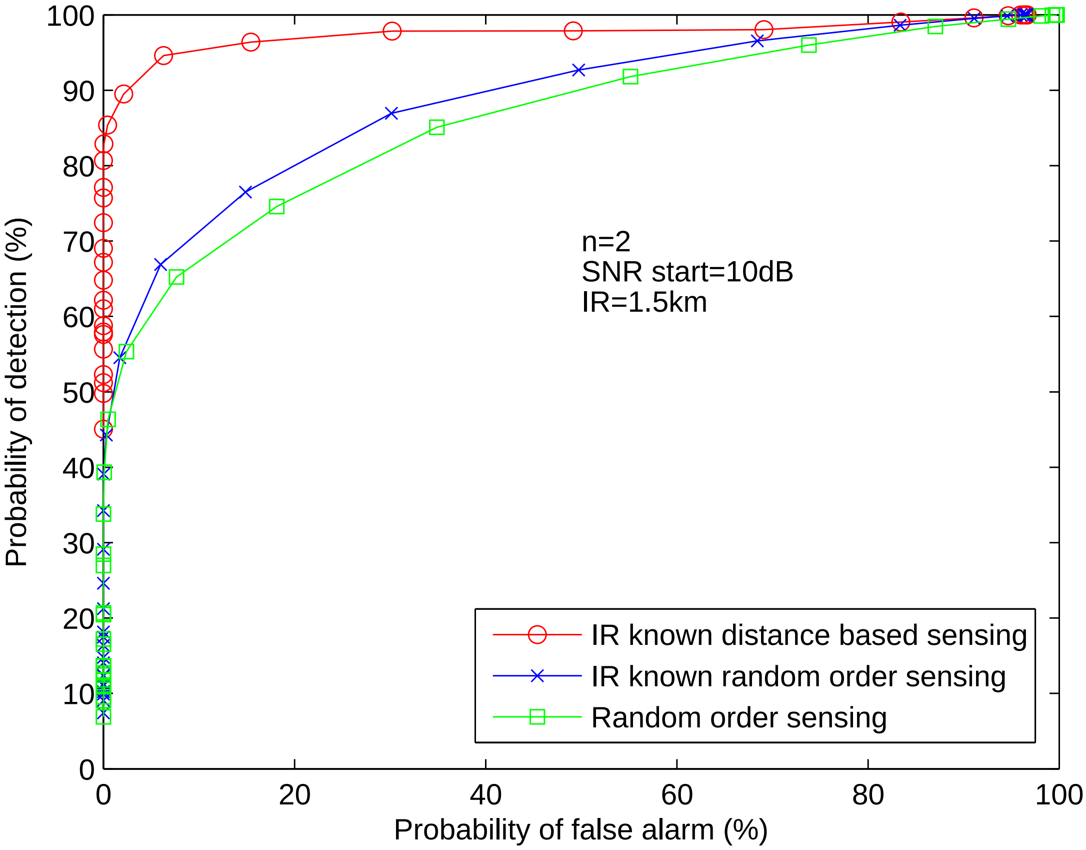

Figure 4.12. ROC curve result for free space environment for IR 1.5 km

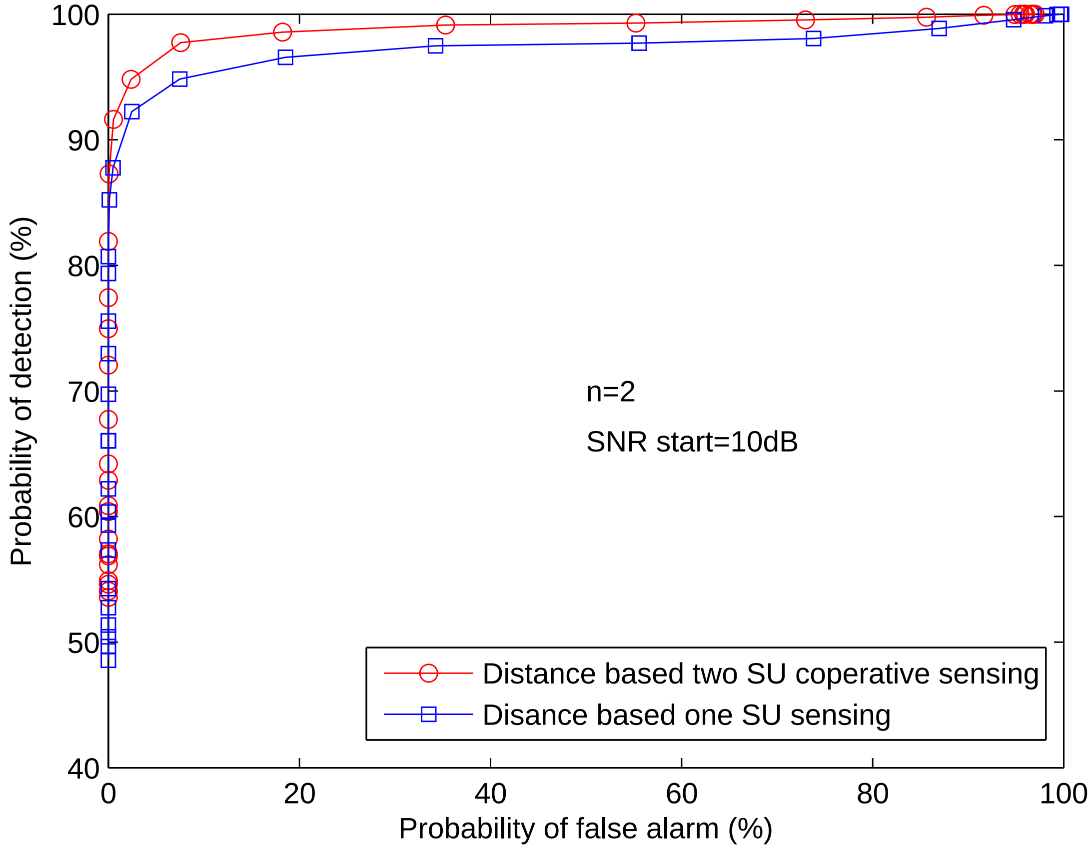

Figure 4.13. ROC curves for two SU cooperative and non cooperative sensing

channel. The maximum IR distance known and maximum IR distance not known simulations are compared in Figure 4.10 for $n = 2$ and maximum IR distance is $1km$.

The effect of interference distance can also be seen on Figure 4.11. Even with only and only maximum interference distance knowledge the performance is highly improved. Using maximum interference distance with the location information gives the highest performance.

We can see the ROC curves when the maximum interference distance is $1.5km$. For higher interference distances, the performance improvement based on this knowledge decreases.

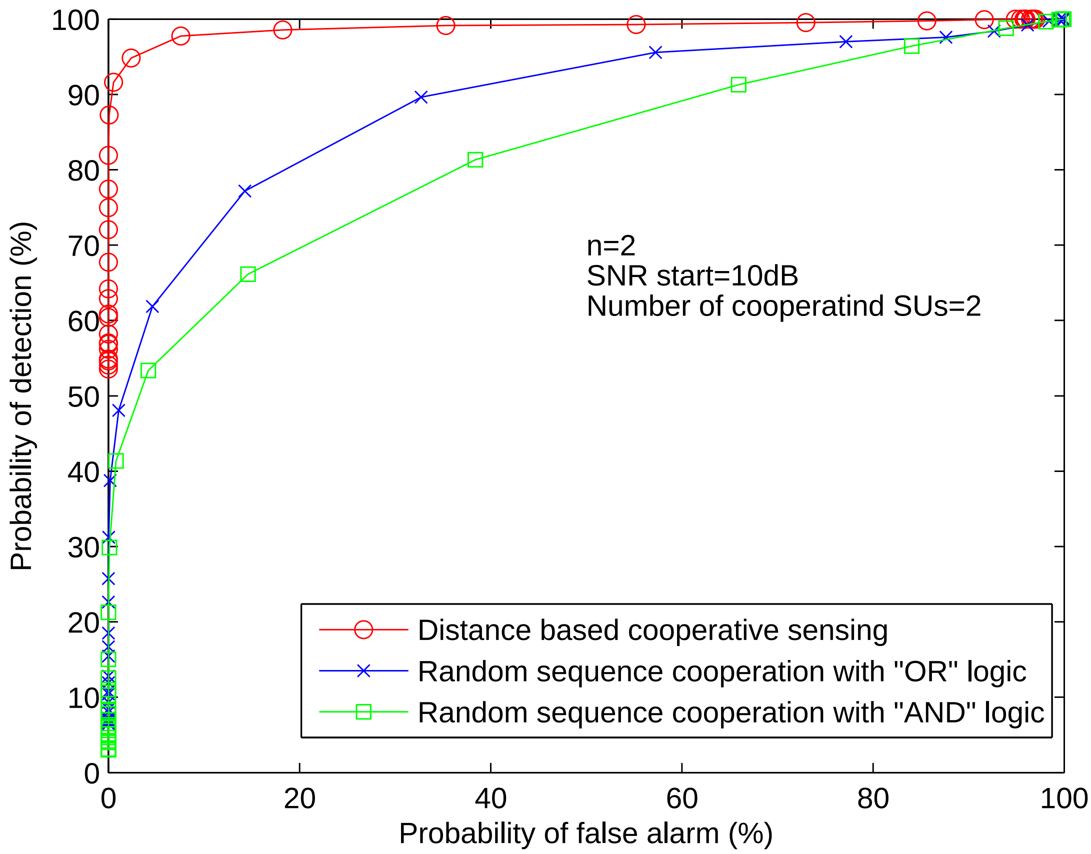

Figure 4.14. ROC curve result for two SU cooperative sensing, ”AND” logic cooperation and ”OR” logic cooperation(n=2)

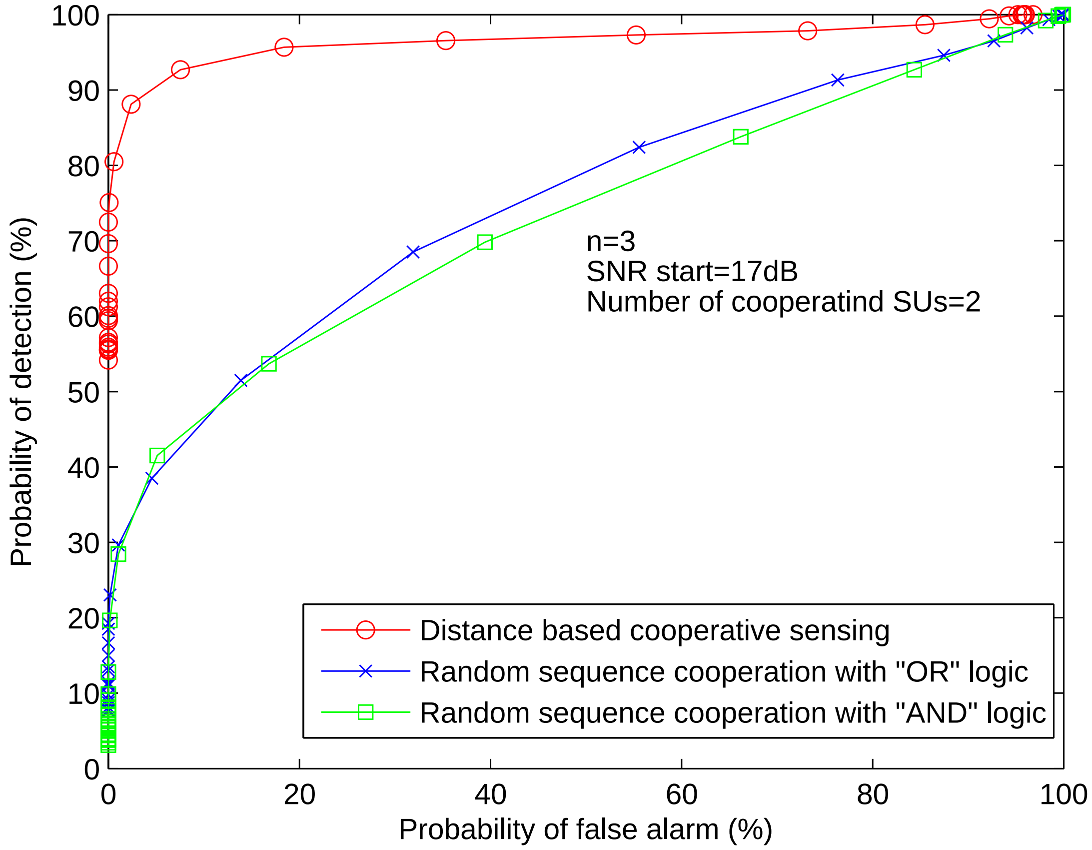

Figure 4.15. ROC curve result for two SU cooperative sensing, "AND" logic cooperation and "OR" logic cooperation(n=3)

4.2.4. Primary User Distance Based Two User Cooperative Sensing

A simple distance based cooperation method is explained in section 3.2.4. Each cognitive user starts sensing individually from the closest primary user to itself and continues with the next closest, if one channel is found as empty, the sensing stops. The performance improvement of cooperation can be seen on Figure 4.13.

The cooperative methods are compered with "AND" logic and "OR" logic cooperation methods. In these methods, the cognitive users senses the same PU, where PUs are sensed in a random order, and uses the logic operators "AND" or "OR" for their one bit decisions, and the sensing stops when a final decision is given as an empty channel. The location based cooperative sensing gives the best result compared to these two methods as it can be seen in Figure 4.14 and Figure 4.15.

5. CONCLUSIONS AND FUTURE WORK

The increasing demand of frequency spectrum introduces the cognitive radio concept. The cognitive radio has to sense the licensed frequency band in order to find an empty channel or detect the presence of the licensed user whose frequency band it is using. Spectrum energy sensing seems to be the most practical way if we will not make any modifications on the primary user systems and it is also adaptive to changing environments. Stopping after an empty channel is found is a practical way for saving battery life.

It is shown that using the inverse relation between distance and SNR, and also the distance information in REM database, the cognitive user can increase the average SNR, hence the sensing performance by sensing from the closest to the furthest. Then, the performance of the proposed method under erroneous distance information in REM database is simulated and it is shown that some distance error does not end up as a fatal problem, the performance of the proposed method is still better than a random method under small errors on the distance information. Then another information about the primary and secondary user systems is assumed to be known. The maximum interference range information, which is the addition of maximum distance that a cognitive user can transmit and the maximum distance that a primary user can transmit, can also be used for increasing sensing performance. When there is a primary user outside that interference range, the cognitive user can use its frequency without sensing it. This also increases the sensing performance a lot. The final proposed method is the cooperation of two users with using primary user location information. Each user starts to sense at the same time from the closest user to itself and stops sensing when an idle channel is found or the next PU is closer to the other SU. This method is also shown to be better than sensing the channels in a random order and using 'and' or 'or' logic operators between the collected answers.

As a future work, a new cooperation scheme can be proposed, or a cooperation scheme for more than two users can be simulated. Weighing according to PU-SU distances or 'choosing according to the closest' algorithms can be implemented. Another thing is, error capability of the proposed method with maximum interference distance known can be shown. Also some of the assumptions such as the equal probability of transmission of primary users or equal transmission power of primary users can be assumed to be untrue and the algorithm can be generalized considering these parameters.

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