Spectrum management and Channel state estimation using Poynting Vector for Cognitive Radio

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Abstract:- The radio frequency spectrum is a scarce natural resource and its efficient use is of the prime importance. The spectrum bands are usually licensed to certain services, such as mobile, fixed, broadcast, and satellite, to avoid harmful interference between different networks. Most spectrum bands are allocated to certain services but worldwide spectrum occupancy measurements show that only portions of the spectrum band are fully occupied. Moreover, there is large temporal and spatial variations in the spectrum occupancy. In the development of future wireless systems the spectrum utilization functionalities will play an important role due to the scarcity of unallocated spectrum. Also the trend in wireless communication systems is going from fully centralized systems into the direction of self-organizing systems where individual nodes can instantaneously establish ad hoc networks whose structure is changing over time. Cognitive radios, with the capabilities to sense the operating environment, learn and adapt in real time according to environment creating a form of mesh network, is seen as a promising technology. Cognitive radio tasks are reviewed with a more detailed discussion on spectrum sensing, frequency and power management functionalities.

Some measurements on current spectrum occupancy are described indicating that even with low overall spectrum occupancy, the spectrum band usage can still frequent and the temporal characteristics need to be identified to find spectrum opportunities. The results include both analysis and computer simulations using Matlab.

The availability of spectrum holes, i.e., frequency bands assigned to a primary user but that are vacant in a given place at a given time, can be estimated with Poynting Vector spectrum sensing technique. When little or no knowledge of the primary user signal is available Poynting Vector based detection is useful. We have studied the performance of an Poynting Vector based detection scheme in terms of probability of detection and probability of false alarm without and with cooperation between the nodes. Cooperative detection by combining the observations of several cognitive radio nodes can be used to improve the performance of spectrum sensing. In addition to the estimation of the availability of spectrum holes, the predicted length of the spectrum holes can be of interest in selecting suitable communication channels. Cognitive radio can learn temporal characteristic of channels over time which will be exploited in intelligent channel selection to improve the performance.

Index Terms— Poynting Vector, cognitive radio, Radio-scene analysis, Channel identification, Dynamic spectrum management and transmit-power control.

1 Introduction

Cognitive radio (CR) is an intelligent wireless communication system that is aware of its surrounding environment, learns from the environment and adapts its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain

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operating parameters in real time [1]. The primary objectives of the cognitive radio are to provide highly reliable communications whenever and wherever needed and to utilize the radio spectrum efficiently. The key issues in the cognitive radio are awareness, intelligence, learning, adaptivity, reliability, and efficiency. The term cognitive radio was first suggested by [2]. He defines the cognitive radio as a radio driven by a large store of a priori knowledge, searching out by reasoning ways to deliver the service the users want [2].The cognitive radio is reconfigurable and built on the software-defined radio (SDR).

The aim of the cognitive radio is to use the natural resources efficiently including frequency, time, and transmitted energy. Spectral efficiency is playing an increasingly important role as future wireless communication systems will accommodate more and more users and high performance (e.g. broadband) services. Cognitive radio technologies can be used in lower priority secondary systems that improve spectral efficiency by sensing the environment and then filling the discovered gaps of unused licensed spectrum with their own transmissions [2], [1]. Unused frequencies can be thought as a spectrum pool from which frequencies can be allocated to secondary users (SUs), for example, in a hotspot [3]. Spectrum pooling radio is a special case of a cognitive radio. Secondary users can also directly use frequencies discovered to be free without gathering these frequencies into a common pool. In addition, CR techniques can be used internally within a licensed network to improve the efficiency of spectrum use.

Transmission techniques for cognitive radio systems include overlay, underlay and interweave [5]. Underlay or interference avoidance model allows concurrent transmission of primary and secondary users in ultra wideband (UWB) fashion where the primary users are protected by enforcing spectral masks on the secondary signals so that the generated interference is below the noise floor for the primary user. However, underlay allows only short-range communication due to the power constraints. Overlay or known interference model also allows concurrent transmission of primary and secondary users. The secondary users use part of their transmission power for relaying the data of primary users and part of the power for their own secondary transmission. In the interweave model the cognitive radio monitors the radio spectrum periodically and opportunistically communicates over the spectrum holes. The focus in this report is in the interweave model. Note that the term overlay is used in many papers, such as [4] to characterize the use of cognitive radios. However, we use the term interweave model to characterize the opportunistic spectrum use with cognitive radios.

The three major tasks of the cognitive radio include [1]:

(1) Radio-scene analysis,
(2) Channel identification, and
(3) Dynamic spectrum management and transmit-power control.

The radio-scene analysis includes the detection of spectrum holes by for example sensing the radio frequency spectrum. The channel identification includes estimation of the channel state information which is needed at the receiver for coherent detection. The transmitter power control and dynamic spectrum management select the transmission power levels and frequency holes for transmission based on the results of radio scene analysis and channel identification. The first two tasks are carried out in the receiver (R_X) while the third task is carried out in the transmitter (T_X), which requires some form of feedback between R_X and T_X.

The cognitive radio is susceptible to emergent behavior due to the time-varying nature of the

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operating environment. Emergence refers to the occurrence of properties at higher hierarchy levels of organization which are not predictable from properties found at lower levels. In CR systems the positive emergent property is the improved area spectral efficiency. Negative emergent properties include possibility to chaotic behavior and traffic jams. The cognitive radio approach can be extended to cognitive networks. A cognitive radio network is an intelligent multiuser wireless communication system that perceives the radio-scene, adapts to variations in the environment, facilitates communication between users by cooperation, and controls the communication through proper allocation of resources [6], [7]. The cognitive network encompasses a cognitive process that can perceive current network conditions, and then plan, decide, and act on those conditions. The network can learn from adaptations and use them to make future decisions taking into account end-to-end goals. Cognitive networks require a software adaptable network to implement the actual network functionality and allow the cognitive process to adapt the network.

The most general theory in telecommunications is information theory which can be classified into syntactic, semantic, and pragmatic levels [8]. Syntactics represents the lowest level which includes the study of relations of signs to other signs. Most of man-made theories are on this level including for example Shannon's statistical information theory. Semantics is the study of the relations of signs to what they represent. This level thus considers the meaning of the signs. Pragmatics represents the highest level which includes the study of the interpretation of signs to their users. This level considers the value and utility of the signs.

The term "cognition" refers to mental processes of perception (sensing), memory, judgment, and reasoning [10]. Thus cognition includes sensoring, memory, processing and reasoning which are the tasks of the cognitive radio. The term "consciousness" refers to awareness of one's own existence, sensations, thoughts, surroundings, etc. [10]. Consciousness includes emotions and free will. Thus, consciousness denotes a higher level of understanding than cognition which is not available in man-made machines. Consciousness denotes the ability to use one's senses and mental powers to understand what is happening. Consciousness indicates a state of awareness of self and environment [11].

II Background

Currently, there is a lot of interest in the research and development of cognitive radios and cognitive radio networks worldwide. Haykin lists the following drivers for the development of cognitive radios in [6]:

- Improved spectrum utilization,
- Regulators (e.g. FCC),
- US Department of Defense,
- International driver examples (e.g. New Zealand with no regulation),
- Standardization bodies (e.g. Institute of Electrical and Electronics Engineers, IEEE) push for the development of new standards with cognitive radio capabilities, and
- Research programs (e.g. Defense Advanced Research Projects Agency, DARPA).

According to [6], future motivators for the development of cognitive radios include the following applications:

- collaborative networks,
- maintenance and fault detection networks,
- self organized networks, and
- cognitive multiple input multiple output (MIMO).

ISSN: 2278 – 1323

In addition, the cognitive radio approach can be useful in other applications such as home environment, utilization of vacant TV bands, messaging devices and other non-real time communication systems. The cognitive radio could improve communications in emergency situations when the traditional network becomes congested with calls for help due to the limited availability of spectrum bands.

Cognitive radio is inspired by cognitive science whose roots date back in 1956 with two scientific events [7]:

- Symposium on Information Theory at Massachusetts Institute of Technology (MIT) in 1956. As a result, the language of information processing was started
- The Dartmouth Conference at Dartmouth College, New Hampshire 1956. The conference concentrated on intelligent machines and led to the development of neural networks.

In response to the scarcity of unallocated spectrum, the FCC has defined four different scenarios about how to improve spectrum access and efficiency of spectrum use by cognitive radio technologies [12]:

1. A licensee can employ cognitive radio technologies internally within its own network to increase the efficiency of use.
2. Cognitive radio technologies can facilitate secondary markets in spectrum use, implemented by voluntary agreements between licensees and third parties. For instance, a licensee and third party could sign an agreement allowing secondary spectrum uses made possible only by deployment of cognitive radio technologies. Ultimately cognitive radio devices could be developed that “negotiate” with a licensee’s system and use spectrum only if agreement is reached between a device and the system.
3. Cognitive radio technologies can facilitate automated frequency coordination among licensees of co-primary services. Such coordination could be done voluntarily by the licensees under more general coordination rules imposed by Commission rules, or the Commission could require the use of an automated coordination mechanism.
4. Cognitive radio technologies can be used to enable non-voluntary third party access to spectrum, for instance as an unlicensed device operating at times or in locations where licensed spectrum is not in use.

The focus in this report is in the fourth scenario. In this scenario the radio can sense and be aware of its environment and can learn from its environment for the best spectrum and resources utilization. The radio can exploit today’s situation so that existing systems remain unchangeable. Every cognitive system is adaptive but every adaptive system is not necessarily cognitive. Thus, cognition leads to adaptation but not necessarily vice versa.

III Challenges in cognitive radios and networks

The cognitive radio has no sense of sight which severely limits the ability to detect the environment. This can lead to the hidden terminal problem where the sensing secondary user is unaware of the presence of a primary user because it cannot reliably detect its presence. A PU terminal and a SU terminal can be separated by some physical obstacle opaque to radio signals. They can also be out-of-range of each other so that the reliable sensing of primary transmission becomes impossible. Two such terminals are said to be hidden from each other [13].

One example of hidden terminal problem is a digital TV which lies at the cell edge where the power of received signal can be barely above the sensitivity of the receiver [14]. If the CR is not capable of detecting TV signal, it can start to use

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the spectrum and interfere with the signal the digital TV is trying to decode. This problem can be avoided if the sensitivity of CR outperforms primary user receiver by a large margin [15], [14].

The hidden terminal problem is also present in WLAN systems which operate on open bands. In WLANs based on the IEEE 802.11 standard, the problem is tackled by using carrier sense multiple access with collision avoidance (CSMA/CA) scheme as the multiple access method. In CSMA/CA a station wishing to transmit first listens to the channel and only transmits if the channel is sensed “idle”. If the channel is sensed busy before transmission, the transmission is deferred for a random interval, which reduces the probability of collisions on the channel.

In a non-cooperative game, the hidden terminal problem can cause unpredictable moves and thus lead to a bad situation. Cooperation and distributed methods help to avoid hidden terminal problem and thus reduce interference to the primary system. Access point (AP) is needed in an ad hoc wireless network to realize control-theoretic cooperation between secondary users. Spectrum sensing information of the nodes will be handled and combined in the access point [3]. Based on that information the occupancy vector is defined and distributed to the nodes in the network. Occupancy vector can be a simple binary vector in which 1 refers to the channel in use and 0 for a free channel. In a four-channel system where only the second channel is free, the occupancy vector is 1011.

It is not adequate to determine whether a band is free. The cognitive radio must also estimate the amount of interference and noise that would exist in the free sub band to make sure that the transmission power of the cognitive radio does not violate the interference limit of the system. The complexity of the cognitive radio is an important aspect. The benefits from the use of cognitive capability must exceed the cost of introducing the cognitiveness which inherently adds to the complexity of the system.

The cognitive radio must be capable of operating over wide bandwidths because the spectrum holes can be spread over large bandwidths. The cognitive radio must be able to sense wide bandwidths as well as transmit on wide range of bandwidth, which places challenges on the antenna design. In particular, the transmission may be spread to several narrow sub-bands and the emission to adjacent bands which are used by the primary users must be avoided.

In a cognitive network information is exchanged between the nodes. The amount of control information is an important issue since the transmission of the control information can become the bottleneck if the amount of control information is large. In an ad hoc network of cognitive radios, all control information is sent over the wireless links resulting in significant traffic amounts if not properly planned.

The emergent behavior apparent in the cognitive network due to the adaptations in the time-varying operating environment is a key issue. When a set of adaptive equipment are connected, the uncontrolled adaptations can lead to fundamental problems. Emergent behavior in cognitive radios can be classified into:

1. Positive emergent behavior, which is characterized by order, and
2. Negative emergent behavior, which is characterized by disorder (e.g. traffic jams and chaotic behavior).

It is important to be able to detect negative emergent behavior which is difficult. In positive emergent behavior predictability is easier.

The goal of the spectrum sensing is to decide between the two hypotheses, namely

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$$x(t) = \begin{cases} n(t) & H0 \\ hs(t) + n(t) & H1 \end{cases}$$

where x(t) is the complex signal received by the cognitive radio, s(t) is the transmitted signal of the primary user, n(t) is the additive white Gaussian noise (AWGN) and h is the complex amplitude gain of the ideal channel [16]. If the channel is not ideal, multiplication of h and s(t) will change to convolution. H0 is a null hypothesis, which states that no licensed user is present in a certain spectrum band. H1 is the alternative hypothesis which indicates that some primary user signal exists[17].

IV Simulation results

In the Monte Carlo computer simulations, the Poynting Vector method has been studied in the frequency domain. Each simulation scenario is repeated 105 times. A complex AWGN channel and one QPSK signal are used in the simulations. The SNR = E/N0 values were -7, -2 and 3 dB. Used FFT length NFFT, which corresponds to the segment length and rectangular window, are 512 or 1024. When we do not use overlapping, block lengths Nb are 205 and 410 symbols for FFT sizes 512 and 1024, respectively. And correspondingly when using overlapping Nb is 116 or 231. In the analysis and simulations we use T = 20. Figures 1 to Figure7 present theoretical and simulated receiver operating characteristic curves for the Poynting Vector method. The theoretical ROC curve is obtained using equation (20), (24) and (26) from [17]. In Figure 1, there are theoretical and simulated ROC-curves for one segment and eight segments when detecting one QPSK-signal. The signal-to-noise ratio is -7 dB. N_{FFT} is 1024. In this case the number of frequency bins to be averaged around the zero frequency L is 10. We compare two cases. In the first case we use only one segment which corresponds to method. In the second case we use 8 non-overlapping segments. It can be seen that the performance is better when using 8 non-overlapping segments. In Figure 2 is also one QPSK signal detection situation when SNR is -7 dB and N_{FFT} is 1024. In this case the number of frequency bins to be averaged around the zero frequency L is 1. Now we can see that performance is worse compared to case when L = 10. In Fig 3 case we have used FFT length 512. Comparing Figures 1 and Figure 3 we can notice that the length of FFT has no effect on the performance.

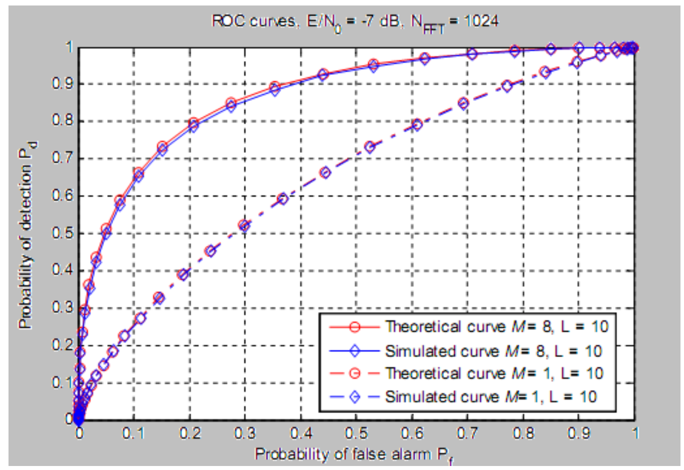

Figure 1:- Receiver operating characteristic. FFT = 1024, SNR = -7 dB

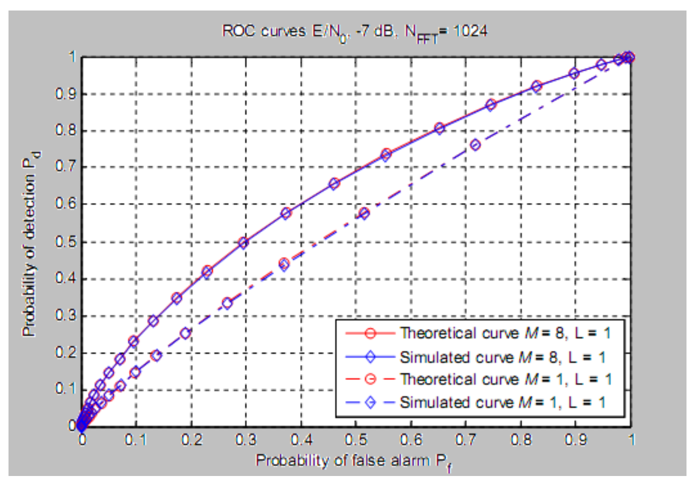

Figure 2:- Receiver operating characteristic. FFT = 1024, SNR = -7 dB

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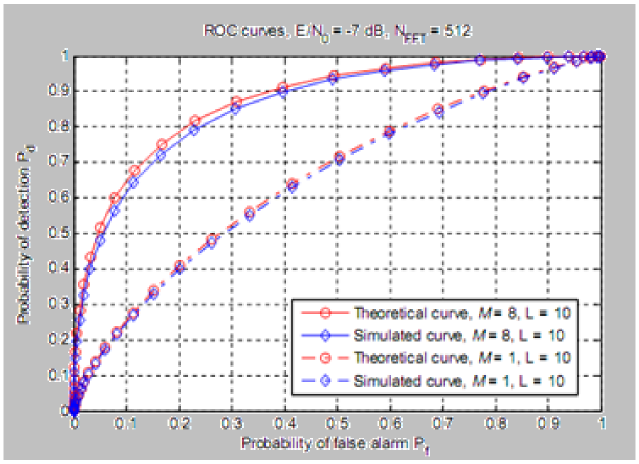

Figure 3:- Receiver operating characteristic. FFT = 512, SNR = -7 dB

In Figure 7 also overlapping case is presented for eight segments and the packet length Np is now 231 samples. In non-overlapping case Np is 410 samples. the segments are overlapping on each other by half of the N_{FFT} samples. We can notice that when using overlapping the performance is almost the same as without overlapping but now the length of the packet can be much smaller.

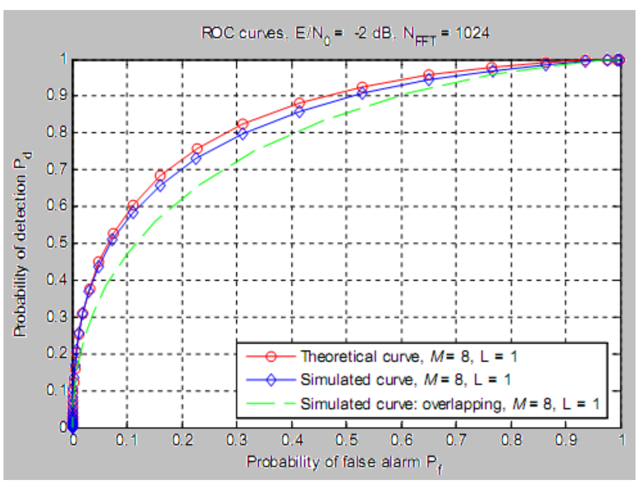

Figure 4:- Receiver operating characteristic. FFT = 1024, SNR = -2 dB

Fig. 7 shows ROC-curves when NFFT = 1024, SNR = 3 dB, L = 1 or 10, and in overlapping case M = 8 or 15 We have also simulated case where M = 15 and Np = 205, i.e. the packet length corresponds to case when we do not use overlapping. We clearly see performance improvement when we compare overlapping case with 15 segments to non-overlapping case with eight segments. Figs. 5 and 6 present overlapping and non-overlapping cases when N_{FFT} = 512, SNR = -7 dB, L = 1 or 10, and in overlapping case M = 8 or 15. When using L =1, we can see that performance is worse compared to the case when L = 10. In addition, simulations show that we can achieve small gain using overlapping compared to the non-overlapping case. However, even with the averaging and overlapping the probability of detection is low with low probabilities of false alarm.

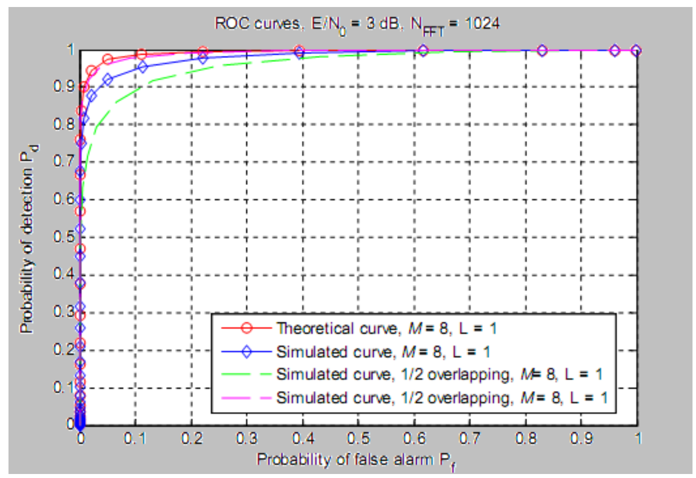

Figure 5:- Receiver operating characteristic. FFT = 1024, SNR = 3 dB

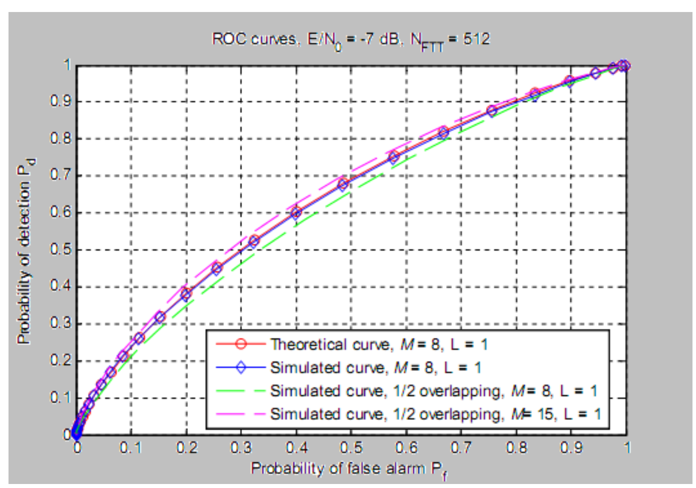

Figure 6:- Receiver operating characteristic. FFT = 512, SNR = -7 dB

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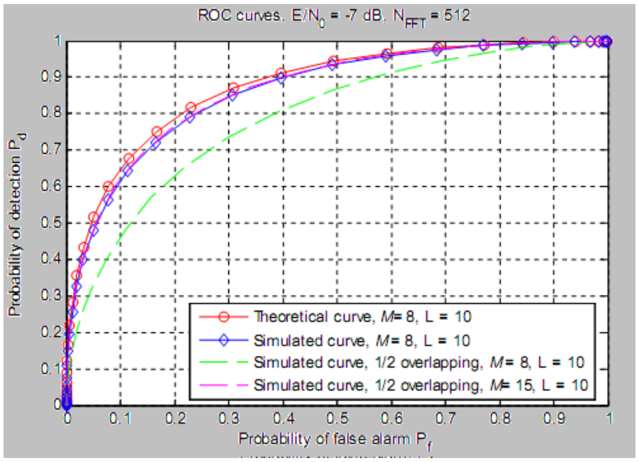

Figure 7:- Receiver operating characteristic. FFT = 512, SNR = -7 dB

Each radio detects the presence of the primary user signal using the model presented in Figure 8.

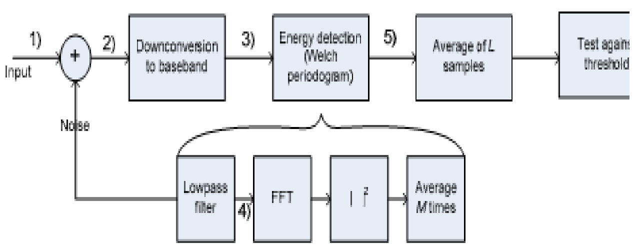

Figure 8:- Simulation Model

The nodes selected for cooperation perform local hypothesis test and send binary value to sensing node indicating whether they believe that the channel is occupied or not. The sensing node combines decisions from cooperating radios using simple or-rule: if one of the cooperating radios detects a primary user, the decision is made that primary user is present. The joint probability for detection Qd and false alarm Qf can therefore be given as

$$Q_d = 1 - (1 - P_d)^{n_{RC}} \qquad (1)$$

$$Q_f = 1 - (1 - P_f)^{n_{RC}} \qquad (2)$$

where Pd and Pf are probabilities of detection and false alarm from a single user, calculated using (20) and (26), respectively from [17]. Signal-to-noise ratio E/N0 = -7 dB and QPSK signal is assumed. The segment length in all cases corresponds to the length of FFT, NFFT, and averaging is done over ten middle FFT samples (L = 10). The average is compared to a decision threshold, which is changed so that the whole range from 0-100% probabilities of false alarm and detection are obtained.

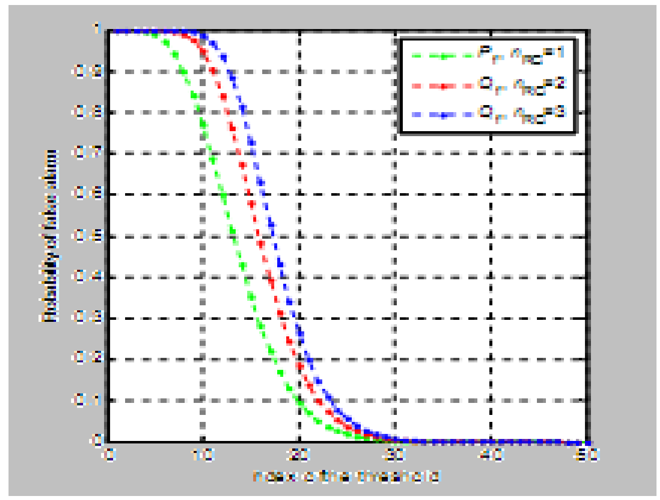

Figure 9:- Probabilities of false alarm for one segment of length NFFT = 512.

The minimum and maximum values for the threshold are selected separately for each simulation and probabilities of false alarm and detection for 50 equally spaced threshold values between the minimum and the maximum are investigated.

In Figure 9, the probabilities of false alarm Pf and In Figure 10, the probabilities detection Pd are shown for the method with one segment (M = 1) of length N_{FFT} = 512. When only one segment is considered, the block length equals to the segment length. It can be seen from the figure that by increasing the number of cooperating radios, both the probability of false alarm and the probability of detection are increased

The theoretical curves, calculated with Equations (20), and (26) from [17], and equation (1) and (2), are shown for comparison. In the figure,

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approximately 1 percentage unit difference can be seen between the theoretical and the simulated curves. This can be explained by the fact that the theory assumes that the non-centrality parameter is constant, whereas in the simulations the non-centrality parameter is a random variable. It converges to a constant value when the number of segments approaches infinity. Thus, the accuracy of the theory improves asymptotically. The theory also neglects the effect of aliasing. From the figure we can see that with 20% probability of false alarm the increase in probability of detection Pd is 5 and 8 percentage units for two and three cooperating radios, respectively.

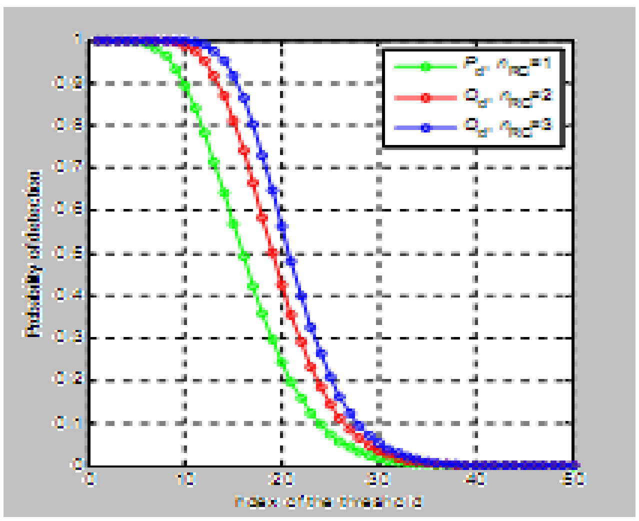

Figure 10:- Probabilities of detection for one segment of length NFFT = 512.

V Conclusions from spectrum sensing

We have studied Poynting Vector based from a spectrum sensing and cognitive radio perspective. We generalized and applied the previous theoretical analysis of the energy detection to the Poynting Vector method. Furthermore, we extended our study to cooperative spectrum sensing. The simulations show that Poynting Vector based signal detection method operates well for narrowband signals. Simulations confirm that Poynting Vector based enhances the performance of the method method. The main limitations of the method yield from the variance. The method is an inconsistent spectral estimator which means that it continues to fluctuate around the true PSD with a nonzero variance. This effect cannot be eliminated even if the length of the processed sample increases without a bound. Furthermore, the fact that the method values are uncorrelated for large number of the processed samples makes the method exhibit an erratic behavior.

From the results on cooperative sensing presented here it can be concluded that the highest increase in probability of detection is observed when moving from single cognitive radio to two cooperating radios, however, adding phenomena such as shadowing, multipath fading, or hidden terminal problem to the simulation model would add the unreliability of the sensing information and could therefore lead into results favoring more extensive cooperation between users. This would lead to a trade-off between reliable sensing information and the costs caused by more extensive cooperation - such as complexity and increased signaling. Adding shadowing would bring up another trade-off on the distance between the cooperating radios. Decreasing the distance would lead to lower delays; however, correlation of shadowing - caused by two radios being blocked by the same object - would degrade the performance of cooperative sensing when radios are close to each other. This would lead to the development of algorithms for finding the optimal radios for cooperation from the candidates. Before mentioned problems are not covered here, however, they are interesting topics and subjects for future research.

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ISSN: 2278 – 1323

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