Distributed Collaboration for Effective Cognitive Radio Networks Implementation

Obeten O. Ekabua
Department of Computer Science
North-West University, Mafikeng Campus,
Private Bag X2046, Mmabatho 2735, South Africa
(*obeten.ekabua@nwu.ac.za*)

Nnenna C. Eric-Nwonye
Department of Computer Science
North-West University, Mafikeng Campus,
Private Bag X2046, Mmabatho 2735, South Africa
(23989696@nwu.ac.za)

Abstract: *Cognitive radios are radios that easily adapt to their operating environment making it possible for unlicensed users to temporarily access, or make use of a licensed frequency spectrum when the licensed user is not using it. This therefore calls for methods that will ensure that the unlicensed user's activities or transmissions, does not interrupt or degrade the licensed user's activities. The ability to reliably identify idle frequency bands is a challenge to individual radios due to the random nature of mobile networks. Radios therefore need to collaborate for performance improvement. Reported in this paper is the development of algorithms for collaborative spectrum sensing, relaying and neighbor selection amongst cognitive radio networks. Included also, is the design of a distributed collaboration strategy for spectrum sensing, through the formation of cognitive coalitions for users to autonomously collaborate and self-organize into independent coalitions, in order to maximize their detection capability. Additionally, we introduce proactive networking protocols such as Destination-Sequenced Distance Vector (DSDV) and Optimized Link State Routing (OLSR), for the radios' communication, relaying and neighbor selection. Finally, for the proposed collaboration strategies to be effective, protocols for auto configuration, spectrum coordination and management were introduced, so that the collaborating radios can conduct their activities in a conflict- free, fair and organized manner.*

1. Introduction

Cognitive radios (CR) are radios or wireless devices capable of sensing and reacting to its operating environment by dynamically adapting itself for good application and network performance. CR improves spectrum efficiency, spectrum utilization, and make spectrum available to new technologies by operating on unused spectrum channels in their local neighborhoods without disrupting the operations of licensed users [1]. The rapid growth and explosion of wireless communications has made the problem of spectrum utilization more critical, creating an ever increasing demand for more radio spectrum [1, 11]. The increasing diversity of communication applications have resulted in overcrowding of the allocated spectrum bands and scarcity of spectrums, resulting to poor service delivery and network problems.

Spectrum is a finite resource which is carefully managed nationally and internationally. This is done by statically allocating spectrum bands for certain users and for delegated use. The downside of static allocation of frequency bands is that it leads to very inefficient use of the spectrum, because many allocated frequency bands are significantly underutilized. This allocation of spectrum bands has created a spectrum shortage that hinders the growth of new wireless applications.

Cognitive radios are the ideal solution to the spectrum scarcity problem because they are radios with the ability to reliably and autonomously identify unused frequency bands. Cognitive radios allow for usage of idle licensed frequency bands by unlicensed (cognitive) users [4]. In order to allow for maximization of spectrum utilization in cognitive radios, it is necessary not to allow unlicensed users to cause interruption or degradation of service to the original license holder. The unlicensed (secondary) users need to monitor the spectrum activities continuously to find a suitable spectrum band for possible utilization and to avoid possible interference to the licensed (primary) users [5, 11].

This spectrum monitoring is mostly done through spectrum sensing, which must be performed before the cognitive users use the licensed spectrum. Spectrum sensing have been identified as a key enabling functionality to ensure that cognitive radios would not interfere with the primary user, by reliably detecting primary user signals. It relies on the secondary systems to identify free spectrum, through direct sensing of the licensed bands [1, 7].

However, the primary signal may be weak or faded, resulting in degraded signals which will be difficult for individual cognitive radio to detect. The two major sources of degraded signals are multipath and shadowing. For example, a cognitive radio can assume the absence of a primary user if it does not see energy in a particular band, which might be a mistake if the cognitive radio suffers severe shadowing with respect to the primary transmitter. Also, in fading channels, single radio sensing requirements are set by the worst case channel conditions introduced by multipath, shadowing and local interference. These conditions could easily lead to a situation where detection of the primary signal will not be possible [4, 12].

These conditions can be avoided if multiple radios share their individual sensing measurements. Each cognitive radio node has only limited local observation to the whole spectrum due to various constraints, therefore, collaboration among cognitive radio nodes are important for acquiring the complete spectrum information. Cooperative spectrum sensing is conducted among cognitive users so as to detect the primary user accurately.

The presence of multiple radios help to reduce the effects of severe multipath at a single radio since each radio will give an independent result of the same situation. With multiple sensing, the probability that all cognitive radios will see deep fades is extremely low. Cooperation allows radios to achieve spectrum sensing robustness to fading environments without drastic requirements on individual radios.

Cooperative communication techniques with cognitive radios hold the promise of promoting efficient spectrum usage and sharing. Also, collaboration among cognitive radios solves the problems of the main challenges of primary user activity detection, which is an important issue in cognitive radio network implementation [4, 10, 12].

2. Dynamic Configuration for Collaboration

Collaboration among cognitive radio networks is increasingly regarded as a key technology for tackling the challenges of a practical implementation of cognitive radio and also for significant performance improvement. Cognitive radios can collaborate through exchange of information, performing tasks cooperatively, negotiating with peers and using peer information to determine their operating settings.

Presented in this paper, are distributed collaboration approaches and algorithms for collaborative spectrum sensing and signal processing, relaying, and service discovery, using various networking protocols. For spectrum sensing, the radios are organized into groups or coalitions with one of the radios as the cognitive head (CH) of each coalition. The radios are working in a distributed fashion, therefore there is no base station, and instead another cognitive radio will act as the coordination channel for information exchange and organization amongst the different coalitions. The radios determine the occupancy state of the spectrum by comparing it to a set threshold.

This paper also provides a method for information exchange whereby, the cognitive nodes use proactive protocols such as Destination-Sequenced Distance Vector (DSDV) and Optimized Link State Routing (OLSR), for relaying, communication and neighbor selection. The radios communicate with each other, update their status and obtain updated information about other radios, using DSDV which is a table-driven protocol. OLSR protocol is used by the radios for neighbor selection and relaying information.

3. Collaborative Spectrum Sensing and Signal Processing

During spectrum sensing, the cognitive radios form different coalition groups with one of the radios as the coalition head of each coalition. Another cognitive radio also serves as a coordination channel or collection point for the whole coalition. This coordination channel is needed to enable the exchange of information among the coalitions. Different users sense the spectrum and share their sensing results or measurements locally and will cooperatively decide on the occupancy of the spectrum. Each radio’s signal and local measurement is collected and sent to the coalition head where it is processed into a decision regarding the occupancy state of the primary band. The local decision is made by comparing the results with a prefixed threshold Y. The decision in turn will be broadcast to all cognitive users in the coalition.

To buttress this point, let us represent spectrum sensing and signal processing as follows:

let;

Y = a set threshold

S = result obtained from sensing the spectrum

if S > Y then Primary User is Present

else

if S < Y then Primary User is Absent

Each radio sends its local decision to the coalition head of their group, the result obtained is Boolean in nature (ie 0 signal is absent, and 1 signal is present), based on the predetermined set threshold Y. If n number of radios combines independent local measurements, then probability of correctly detecting the status of the system increases. The set threshold Y will be used to determine and measure the reliability of the collected results. When the collected signal S_i exceeds the threshold Y, decision 1 will be made which assumes that the primary user is present; otherwise, decision 0 will be made.

Every cognitive user *i*, for *i* = 1, . . ., N, conducts spectrum sensing individually and collects the energy S_i. It then reports to the coalition head, a decision D_i, which is given by

$D_i = 0$; where $0 < S_i < Y$

and

$D_i = 1$; where $S_i > Y$

The coalition head will then make a decision based on the measurements received from each radio in the coalition and send to the coordination channel. Let us assume that the coordination channel receives *k* out of *N* local decisions reported from the coalition heads, it will then make a final decision. The spectrum is assumed to be available only when all the *k* reporting decisions are 0.

Below is an algorithm for distributed collaborative spectrum sensing. This algorithm is used to construct a framework for spectrum sensing.

3.1 Distributed Collaborative Sensing Algorithm

For the proposed distributed collaborative sensing method, let us establish an algorithm as follows:

Initial State: CR = { CR1,. . ., CRN}

CR1 = {CR11,. . ., CR1N}

.

.

.

CRn = {CRn1, . . . ,CRnN}

Where CR1 to CRn are each a coalition made up of n number of cognitive radios. The algorithm is grouped into four stages and different activities takes place during each stage.

Stage 1: Individual Sensing

During individual sensing stage, each individual cognitive radio senses the spectrum and computes its local spectrum sensing observation or result for reporting to the coalition head.

Stage 2: Sensing Result Processing by the Coalition Head

In the second stage, each cognitive radio will report its sensing result to the coalition head, who compiles and processes the signals received from each cognitive radio in the coalition.

The coalition head then makes a tentative Boolean decision of 0 or 1 based on the signals. The signal bit and decision are then sent to the coordination channel

Stage 3: Coordination Channel Decision

During the third stage, the coordination channel receives signal bits and results from each coalition head, compares the results received with the prefixed threshold Y and then make a final Boolean decision of 0 or 1 on the occupancy state of the spectrum

Stage 4: Coordination Channel Broadcast

In stage four, the coordination channel broadcasts the decision to the coalition heads who in turn broadcasts the message to each radio in their coalition. Finally, it updates the spectrum database with the new result.

4. Channel Monitoring

During channel monitoring, each cognitive radio node is equipped with transceivers, which are used for spectrum monitoring and for distributing sensing results over to the coalition head (Fig 1). The spectrum monitor will keep detecting any active signals in the specified frequency range and will also update a signal database continuously. Once the primary user appears, the secondary receiver will pick the best available channel from the spectrum database to continue previous communication.

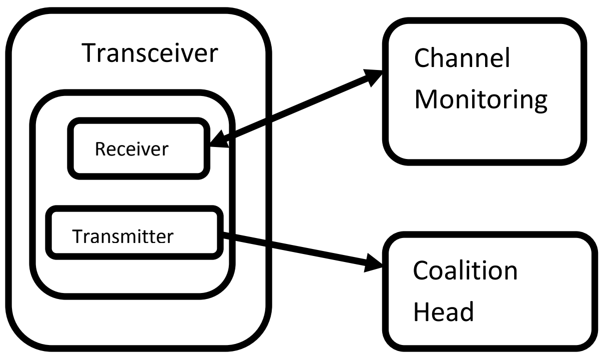

Fig 1: Channel Monitoring

Channel monitoring is done using Energy detection and Cyclostationary detection methods. The radios use an energy detector to measure the energy received on a primary band and use cyclostationary detector to differentiate primary signal from noise and interference. The cognitive radio nodes access the licensed bands in two phases; the sensing phase and the transmission phase. In the sensing phase, a cognitive radio node senses the channel using its receiver and then exchanges sensed channel information with other cognitive radio nodes and the coalition head using the transmitter.

5. Neighbor Detection and Multipoint Relay (MPR) Selection

For neighbor detection and multipoint relay selection, the radios use proactive protocols such as Destination-Sequenced Distance Vector (DSDV) and Optimized Link State Routing (OLSR) for regular exchange of topology information with other nodes in the group. DSDV is a table driven protocol therefore, each radio node advertises to its neighboring nodes in the coalition group its own routing table and information. This is done periodically and each new update must have a sequence number (time stamp) so that receiving nodes can distinguish old information from current information.

OLSR enables it to work in a completely distributed manner without depending on any central entity and makes it possible for nodes to broadcast messages. The nodes would broadcast ‘Hello’ messages which are used for neighbor detection. They detect their neighbors through link sensing which is accomplished through periodic emission of ‘Hello’ messages over the interfaces. Individual nodes can use this topology information to compute next hop destinations for all nodes in the group using shortest hop forwarding path. It then selects its multipoint relays (MPR) based on the one hop node that offers the best routes to the two hop nodes.

The idea of multipoint relays (MPR) is to minimize the overhead of flooding messages in the network by reducing redundant retransmissions in the same region. Each node in the network would select a set of nodes in its symmetric one-hop neighborhood, which may retransmit its messages. This set of selected neighbor nodes is called the MPR set of that node. The neighbors of node A which are not in its MPR set would be able to receive and broadcast messages but would not retransmit broadcast messages received from node A.

Each node selects its MPR set from among its one-hop symmetric neighbors. This set is selected such that it covers all symmetric two-hop nodes in terms of radio range. Each node maintains information about the set of neighbors that have selected it as an MPR. A node will obtain this information from periodic ‘Hello’ messages received from the neighbors. Upon receipt of this MPR selector information, each node will calculate and update its route to each destination. The objective of MPR selection is for a node to select a subset of its neighbors such that a broadcast message, retransmitted by these selected neighbors, will be received by all nodes two hops away from it (fig 2).

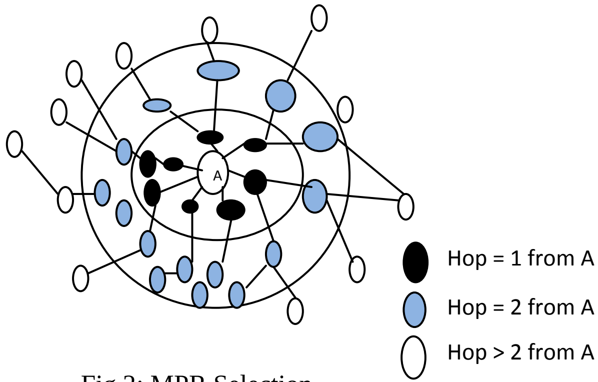

Fig 2: MPR Selection

The ‘Hello’ messages will include the sender’s identifiers and the identifiers of its k-hop neighbors. With this information, a cognitive radio device knows the nodes with which it can directly communicate with over the channel or that it can reach in up to n hops. For the proposed MPR selection, an algorithm is derived below.

5.1 Neighbor Detection and MPR selection Algorithm

For nodes to identify their neighbors and select nodes to relay their messages, we propose an algorithm as follows:

Stage 1: Node Advertisement

Coalition 1 = {CR11, . . . , CR1n}

Coalition 2 = {CR21, . . . , CR2n}

.

.

.

Coalition N = {CRN1, . . .,CRNn}

The activities involved in neighbor detection are also grouped in stages beginning with nodes advertising their routing tables.

In the first stage, a node, ‘A’ sends information and advertises its routing table with a sequence number added to each advert for other nodes

Stage 2: Receiving Nodes

During the second stage, each neighboring node receives the broadcast and then transmits its response back to Node A

Stage 3: Link Sensing and Neighbor Discovery

In the final stage, Node A processes the responses and identifies its one hop neighbors. Through its one hop neighbors, it identifies its two hop neighbors and finally selects its Multipoint Relay (MPR) node.

6. Cognitive Relay

For relaying signals and messages amongst the radios, each coalition group is created with agreement to forward each other’s packets. One node (the relay) forwards the transmission received from another node (the source) towards its destination. Some packets from the primary user will also be delivered by the secondary nodes, which aim at enhancing secondary throughput through the increase of transmission opportunities for the secondary.

Each cognitive radio node is also utilized as a relay node to convey the signal transmitted from the primary user PU to the coalition head CH (fig 3). The coalition head then relay the signals received to the coordination channel. The idea is to utilize relay nodes to convey the signal transmitted from the primary user to the coordination channel, which will make estimation of the presence or absence of primary activities. Given n cognitive relays between the primary user and the coordination channel; the cognitive relays simultaneously receive primary user’s signal through independent fading channels and each cognitive relay then amplifies the received primary signal and forward to the cognitive head. The relay node uses one of its transceivers to receive data and uses the other transceiver to forward data to its destination (fig 1).

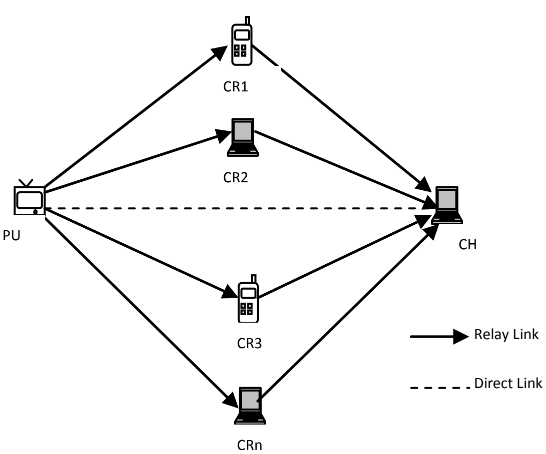

Fig 3: Cooperative Network with Cognitive Relays

7. Service Discovery

During service discovery, the coordination channel broadcasts information about current network status to the cognitive radios. This information is broadcast through table updates and beacons. It also gives information about new radios joining a coalition. The coordination channel also serves as a router between the coalitions and also as router between multiple network layers within each coalition.

A new node joining a coalition listens for beacons and updates on the control channel, to obtain service discovery and connectivity information to initialize its radio parameters. Current nodes will provide performance information in the beacons because as a radio joins a cognitive coalition, connectivity will also be established with the neighboring radios or coalition and a message sent to the neighbors for a service discovery overlay. This allows the new radio to discover how to access all of the various services. The control head then exposes the new radio’s identifier to the coalitions through the appropriate name service. When a node receives a new ‘join’ request or data, it stores the source ID and the sequence number of the packet in its table.

For the purpose of service discovery, the algorithm below is derived.

7.1 Naming and Service Discovery Algorithm

For a node to discover services from the other nodes, we propose an algorithm in two stages as follows:

Let CRnew be a new cognitive node

Stage 1:

During the first stage, CRnew sends a ‘join’ message and joins a cognitive radio coalition

The coalition head sends a message to the neighboring radios and the coalition heads of the neighboring radios sends the service discovery settings to CRnew through beacons

Stage 2:

On receiving the settings, CRnew starts up

It listens for beacons on the control channel and obtains connectivity information from the beacons and tables

And finally, initializes its radio parameters.

8. Local Coordination and Bargaining

For local coordination and bargaining, each coalition of cognitive radios is also a bargaining group and each group modifies spectrum assignment within the group to improve system utility which is measured in terms of proportional fairness among the cognitive radios. Each coalition also performs local coordination to modify their spectrum usage in order to achieve a conflict free spectrum sharing. The coalitions negotiate spectrum usage through message exchanges and the radios exchange information among themselves locally about how to bargain with other coalitions for mutual gain. The radios or coalitions also need to observe the behaviors of neighboring nodes and adjust spectrum usage according to predefined rules. With these, fair solutions for dynamic spectrum access can then be achieved in a self-organized way.

The protocols that will be necessary to make these proposed collaboration strategies effective are:

9. Auto Configuration Protocols

Auto configuration requires a radio node to be aware of itself, the surrounding nodes and current network status when it starts up. In this collaboration approach, It does this by obtaining reachability and performance information by listening for beacons and table update. The new node also negotiates with existing coalitions for name and service discovery. Dynamic channel assignment method is used for communication among the cognitive radio nodes because; the set of available channels could change over time. The distributed MAC-layer configuration will enable nodes to dynamically discover the network topology and physical location of each node in the network. The nodes would invoke the MAC-layer configuration operation periodically to maintain accuracy despite changes in network topology, changes in channel availability set maintained by individual nodes, and node movements. When a radio is turned on, it will remain silent until the first execution of the MAC-layer configuration protocol. During the MAC-layer configuration, time is split into intervals and each interval is further divided into time slots of equal length. A node is allowed to transmit during its allocated timeslot in each interval and all other nodes are in receive mode during that time. This ensures that every node in the network gets a chance to transmit without collisions during each interval.

10. Spectrum Coordination and Management Protocols

Spectrum etiquette and coordination policies are implemented and enforced using the coordination channel. Each radio sends information about spectrum usage through beacons and table update so that neighboring cognitive radios or nodes can avoid using the same frequency. Cognitive radio devices will use the coordination channel routing tables to set up links with other nodes. A message cache is also maintained by each node to detect duplicate messages. All radios will use this policy to communicate with the coordination channel. The coordination channel can obtain information about the environment through measurements and information sent or obtained by different radio terminals. It then proffers suggestion or make decisions for efficient coordination.

Control information exchange among users is important. Channel selection and negotiation for data communication will be done by control information exchanging among users. All users use the coordination channel for information and control packet exchanges. Whenever a user wants to initiate communication with any other user or wants to send data, it will negotiate with the intended receiver by exchanging necessary control information on the coordination channels. Using this method, the radios' activities can be conducted in an orderly and conflict-free way.

11. Conclusion

Cognitive radios are fully programmable wireless devices that can sense and dynamically adapt to their operating environment to enhance system performance. Instead of using statically assigned spectrum, cognitive radios can operate on unused spectrum channels in their local neighborhoods without disrupting the operations of existing spectrum owners (primary users). Frequency bands are statically allocated to certain users for specific use, but most of the allocated frequencies are grossly underutilized while at the same time the emergence of new technologies and applications have placed more demand on the frequency spectrum, causing scarcity of frequency. Cognitive radios attempt to alleviate the problem of inefficient utilization of the frequency spectrum by opportunistically using the licensed bands when the licensed user is not using it. Therefore, reported in this paper is the development of distributed collaboration approaches for cognitive radio networks using updating and table driven networking protocols- Destination-Sequenced Distance Vector (DSDV) and Optimized Link State Routing (OLSR).

For these collaboration strategies to be effective, auto configuration, spectrum coordination and management protocols were introduced. Auto configuration protocol makes a radio node to be aware of itself, the surrounding nodes and network status when it starts up. This is achieved by obtaining reachability and performance information from other radio nodes through beacons and table updates. Spectrum coordination and management is implemented using the coordination channel, which proffers suggestions and makes decisions for efficient coordination.

References

[1]. NSF Workshop Report. Future Directions in Cognitive Radio Network (CRN) Research. March 2009

[2]. Federal Communication Commission (FCC). Spectrum Policy Task Force Report. Report ET Docket No 02 – 135, November 2002. www.fcc.gov/oet/info/database/spectrum/

[3]. Federal Communication Commission (FCC). Notice of Proposed Rule Making and Order. ET Docket No 03 – 322, December 2003. www.fcc.gov

[4]. Amir Ghasemi, Elvino S. Sousa. Spectrum Sensing in Cognitive Radio Networks: Requirements, Challenges and Design Trade-offs. IEEE Communications Magazine, April 2008.

[5]. Jun Ma, Goeffrey Ye Li. Signal Processing in Cognitive Radio. Proceedings of the IEEE, Volume 97, No 5, May 2009.

[6]. Joseph Mitola III. Cognitive Radio: An Integrated Agent Architecture for Software Defined Radios (SDR). PHD

Thesis, KTH Royal Institute of Technology, Stockholm, Sweden, 2000.

[7]. Danijela Cabric, Artem Tkachenko, Robert W Brodersen. Experimental Study of Spectrum Sensing Based on Energy Detection and Network Cooperation.

[8]. Cabric D., S.M Mishara, R.W Brodersen. Implementation Issues in Spectrum Sensing. In Proc, 38th Annual Asilomar Conference on Signal, Systems and Computers. Pacific Grove, CA, USA, November 2004. PP. 772 – 776.

[9]. Cabric D., et al. A Cognitive Radio Approach for Usage of Virtual Unlicensed Spectrum. In Proc. Of 14th IST Mobile Wireless Communications Summit. Dresden, Germany, June 2005.

[10]. Oscar Filio-Rodriguez, et al. Collaborative Spectrum Sensing for Cognitive Radio: Diversity Combining Approach. Wireless Sensor Network, 3, 24 – 37. www.SCiRP.org/journal/wsn. 2011.

[11]. Danijela Cabric, Artem Tkachenko, Robert W Brodersen. Spectrum Sensing Measurements of Pilot, Energy and Collaborative Detection. Berkeley Wireless Research Center, University of California, Berkeley. www.eecs.berkeley.edu. 2003.

[12]. Shridhar Mubaraq Mishra, Anant Sahai, Robert W Brodersen. Cooperative Sensing Among Cognitive Radios. University of California, Berkeley. www.eecs.berkeley.edu.

[13]. Simone O., Gambini J., Bar-ness Y. Cooperation and Cognitive Radios. CWCSPR, NJIT, University Heights, NJ 07102 USA.

[14]. Wireless Working Group. Technical Document on Cognitive Radio Networks. Draft, Version 1.0. September 15, 2006.

[15]. Vibhav Krashan Chaurasiya. International Journal of Enterprise Computing and Business Systems. Volume 1, Issue 2. www.ijecbs.com. July 2011.

[16]. Ying-Chang Lian, et al. Advanced Signal Processing for Cognitive Radio Networks.EURASIP journal on Advances in Signal Processing. Volume 2010, Article ID 715987. January 2010.

[17]. Ghasemi A. and Sousa E. S. Spectrum Sensing in Cognitive Radio Networks: The Cooperation-Processing Trade-Off. Wiley Wireless Communication and Mobile Comp. Special Issue on Cognitive Radio, Software-Defined Radio, and Adaptive Wireless Systems, vol. 7, no. 9, November 2007.

[18]. Zhi Quan, Shuguang Cui, Ali H. Sayed. Optimal Linear Cooperation for Spectrum Sensing in Cognitive Radio Networks. IEEE Journal of Selected Topics in Signal processing. Volume 2, No 1. February 2008.

[19]. Siva Ram Murthy C. and B. S. Manoj. Ad Hoc Wireless Networks, Architecture and Protocols. Prentice Hall. 2008.

[20]. Diomidis S. Michalopoulos and and George K. Karagiannidis. PHY-Layer Fairness in Amplify and Forward Cooperative Diversity Systems. IEEE Transactions on Wireless Communications. Volume 7, No. 3. March 2008.