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Relay Based Cooperation for Cognitive Radio Networks

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Abstract: Spectrum allocation has been traditionally done in a licensed fashion. But observations of spectrum usage suggest that most bands are underutilized. Cognitive Radio (CR), broadly defined as an intelligent radio which can adapt based its context has come up as a means for opportunistic (secondary) usage of spectrum. Cognitive radios are required to sense the spectrum for availability of holes and to communicate in the sensed holes without interfering with the licensed primary users of the bands. According to the network architecture, cognitive radio networks can be classified as infrastructure-based and ad-hoc networks. The infrastructure based networks rely on base-station like controller/arbiters. These arbiters collect the sensing information and decide on the band for secondary communication. The ad-hoc network does not have any infrastructure backbone. So, each user needs to have all CR capabilities and is responsible for determining its actions based on the local observation. One of the most important challenges for cognitive radio systems is to identify the presence of primary (licensed) users over a wide range of spectrum at a particular time and specific geographic location. We consider the use of cooperative spectrum sensing in cognitive radio systems to enhance the reliability of detecting primary users. With multi-hop relay, we enhance coverage, throughput and system capacity.

Key words: Cognitive radio, ad-hoc networks, spectrum management, relay, cooperative spectrum sensing and sharing, India

INTRODUCTION

The radio electromagnetic spectrum being a precious natural resource has to be utilized efficiently. Today's wireless networks are regulated by a fixed spectrum assignment policy, i.e., the spectrum is regulated by governmental agencies and is assigned to license holders or services on a long term basis for large geographical regions.

Also, a large portion of the assigned spectrum is used sporadically as showed in Fig. 1 where the signal strength distribution over a large portion of the wireless spectrum is shown. The spectrum usage is concentrated on certain portions of the spectrum while a significant amount of the spectrum remains unutilized (Akyildiz *et al*., 2006).

According to the report published by the Federal Communications Commission (FCC) prepared by Spectrum-policy task force, one of the major finding reveals the context of spectrum utilization. In many bands, spectrum access is a more significant problem than physical scarcity of spectrum in large part due to legacy command and control regulation that limits the ability of potential spectrum users to obtain such access. In order to address the critical problem of spectrum scarcity, the

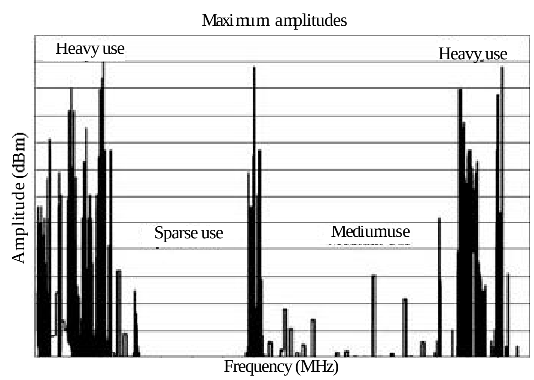

Fig. 1: Spectrum utilization

FCC has recently approved the use of unlicensed devices in licensed bands. Scanning the portions of the radio spectrum including the revenue-rich urban areas, it is found that (McHenry, 2003; Staple and Werbach, 2004):

- Some frequency bands in the spectrum are largely unoccupied most of the time
- Some other frequency bands are only partially occupied
- The remaining frequency bands are heavily used

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The underutilization of the electromagnetic spectrum leads us to think in terms of spectrum holes for which the following definition is offered. A spectrum hole is a band of frequencies assigned to a primary user but at a particular time and specific geographic location, the band is not being utilized by that user. Spectrum utilization can be improved significantly by making it possible for a secondary user (who is not being serviced) to access a spectrum hole unoccupied by the primary user at the right location and the time in question. Cognitive Radio (CR) as an agile radio technology has been proposed to promote the efficient use of the spectrum. By sensing and adapting to the environment, a CR is able to fill in spectrum holes and serve its users without causing harmful interference to the licensed user. To do so, the CR must continuously sense the spectrum, it is using in order to detect the reappearance of the Primary User (PU). Once the PU is detected, the CR should withdraw from the spectrum so, as to minimize the interference, it may possibly cause. This is a very difficult task as the various PUs will be employing different modulation schemes, data rates and transmission powers in the presence of variable propagation environments and interference generated by other secondary users. Another great challenge of implementing spectrum sensing is the hidden terminal problem which occurs when the CR is shadowed in severe multi-path fading or inside buildings with a high penetration loss while a PU is operating in the vicinity.

COGNITIVE RADIO

The term cognitive radio was coined by Joseph Mitola. What do we mean by cognitive radio? According to the Encyclopedia of Computer Science (Ralston and Reilly, 1993), we have a three-point computational view of the term cognition:

- Mental states and processes intervene between input stimuli and output responses
- The mental states and processes are described by algorithms
- The mental states and processes lend themselves to scientific investigations

The cognitive radio, built on a software-defined radio is defined (Haykin, 2005) as an intelligent wireless communication system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier-frequency and modulation strategy) in real-time with two primary objectives in mind:

- Highly reliable communication whenever and wherever needed
- Efficient utilization of the radio spectrum

A cognitive radio is defined as a radio that can change its transmission parameters depending on the environment in order to communicate efficiently. Cognitive radio is a form of intelligent wireless communication in which a transceiver can intelligently detect which communication channels are in use and which are not and instantly move into vacant channels while avoiding occupied ones. The cognitive radio must not cause any kind of interference to the already existing users.

Characteristics of cognitive radio: A spectrum hole is a band of frequencies assigned to a primary user but at a particular time and specific geographic location, the band is not being utilized by that user. Spectrum utilization can be improved significantly by making it possible for a secondary user (who is not being serviced) to access a spectrum hole unoccupied by the primary user at the right location. A cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. From this definition, two main characteristics of the cognitive radio can be defined (Welch, 1967; Basar and Olsder, 1999).

Cognitive capability: Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency band of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.

Reconfigurability: The cognitive capability provides spectrum awareness whereas reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design (Compton, 1988). Since, most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as showed

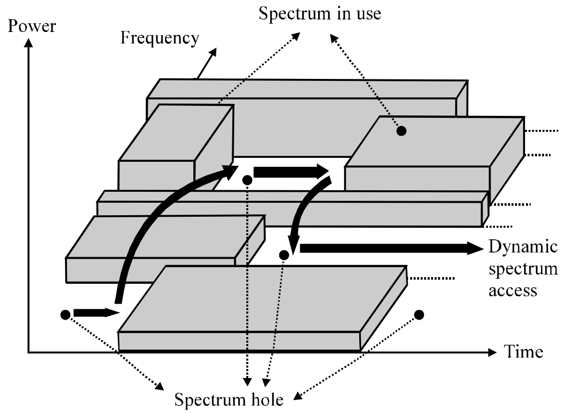

Fig. 2: Spectrum hole concept

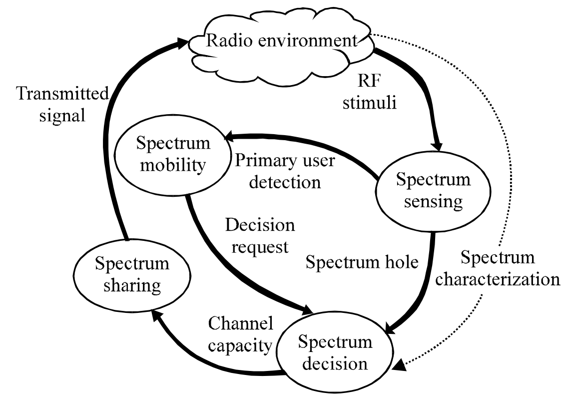

Fig. 3: The cognitive radio cycle

in Fig. 2. The cognitive radio enables the usage of temporally unused spectrum which is referred to as spectrum hole or white space. If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

Cognitive task: Figure 3 shows the basic cognitive cycle (Akyildiz *et al*., 2009). The corresponding spectrum management functionalities are spectrum sensing, spectrum decision, spectrum mobility and spectrum sharing.

Spectrum sensing: Detecting unused spectrum and sharing the spectrum without harmful interference with other users.

Spectrum decision: Capturing the best available spectrum to meet user communication requirements.

Spectrum mobility: Maintaining seamless communication requirements during the transition to better spectrum.

Spectrum sharing: Providing the fair spectrum scheduling method among coexisting CR users.

COGNITIVE RADIO NETWORK ARCHITECTURE

Existing wireless network architectures employ heterogeneity in terms of both spectrum policies and communication technologies. Moreover, some portion of the wireless spectrum is already licensed to different purposes while some bands remain unlicensed.

For the development of communication protocols, a clear description of the CR network architecture is essential. In this study, the CR network architecture is presented such that all possible scenarios are considered.

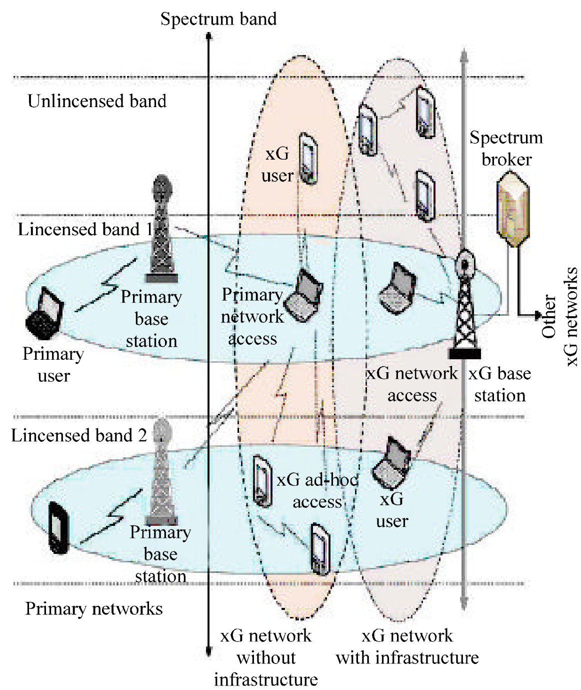

Fig. 4: Cognitive radio network architecture

Also, the term xG (next generation) network (Akyildiz *et al*., 2006) is used to describe the CR network. The components of the CR network architecture as shown in Fig. 4 can be classified in two groups as the primary network and the CR network. The basic elements of the primary and the CR network are defined as follows:

Primary network: An existing network infrastructure is generally referred to as the primary network which has an exclusive right to a certain spectrum band. Examples include the common cellular and TV broadcast networks. The components of the primary network are as follows:

Primary user: Primary user (or licensed user) has a license to operate in a certain spectrum band. This access can only be controlled by the primary base-station and should not be affected by the operations of any other unlicensed users. Primary users do not need any modification or additional functions for coexistence with CR base-stations and CR users.

Primary base-station: Primary base-station (or licensed base-station) is a fixed infrastructure network component which has a spectrum license such as Base-station Transceiver System (BTS) in a cellular system. In principle, the primary base-station does not have any CR capability for sharing spectrum with CR users. However, the primary base-station may be requested to have both legacy and CR protocols for the primary network access of CR users.

xG network: CR network (or Cognitive radio network, Dynamic spectrum access network, Secondary network and Unlicensed network) does not have license to operate in a desired band. Hence, the spectrum access is allowed only in an opportunistic manner. CR networks can be deployed both as an infrastructure network and an ad-hoc network as shown in Fig. 3. The components of a CR network are as follows:

xG user: CR user (or unlicensed user, cognitive radio user and secondary user) has no spectrum license. Hence, additional functionalities are required to share the licensed spectrum band.

xG base-station: xG base-station (or unlicensed and secondary base-station) is a fixed infrastructure component with CR capabilities. CR base-station provides single hop connection to CR users without spectrum access license. Through this connection, an CR user can access other networks.

Spectrum broker: Spectrum broker (or scheduling server) is a central network entity that plays a role in sharing the spectrum resources among different CR networks. Spectrum broker can be connected to each network and can serve as a spectrum information manager to enable coexistence of multiple CR networks. The reference CR network architecture consists of different types of networks; a primary network, an infrastructure based CR network and an ad-hoc CR network. CR networks are operated under the mixed spectrum environment that consists of both licensed and unlicensed bands. Also, CR users can either communicate with each other in a multi-hop manner or access the base-station. Thus in CR networks, there are three different access types:

CR network access: CR users can access their own CR base-station both on licensed and unlicensed spectrum bands.

xG ad-hoc access: xG users can communicate with other xG users through ad-hoc connection on both licensed and unlicensed spectrum bands.

Primary network access: The CR users can also access the primary base-station through the licensed band.

COGNITIVE RADIO AD-HOC NETWORK

According to the network architecture, Cognitive Radio (CR) networks can be classified (Akyildiz *et al*., 2009) as the infrastructure-based CR network and the Cognitive Radio Ad-Hoc Networks (CRAHNs). The infrastructure-based CR network has a central network entity such as a base-station in cellular networks or an access point in wireless Local Area Networks (LANs). The CRAHN does not have any infrastructure backbone. Thus, a CR user can communicate with other CR users through ad-hoc connection on both licensed and unlicensed spectrum bands. In the infrastructure-based CR networks, the observations and analysis performed by each CR user feeds the central CR base-station so that it can make decisions on how to avoid interfering with primary networks. According to this decision each CR user reconfigures its communication parameters as shown in Fig. 5a. In CRAHNs, each user needs to have all CR capabilities and is responsible for determining its actions based on the local observation as shown in Fig. 5b. Since, the CR user cannot predict the influence of its actions on the entire network with its local observation, cooperation schemes are essential where the observed information can

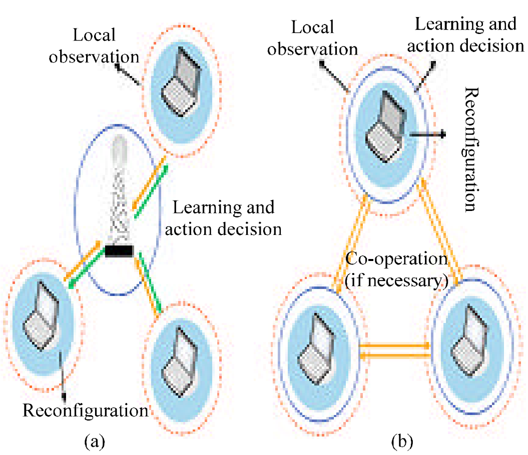

Fig. 5: Comparison between CR capabilities for: a) infrastructure-based CR networks and b) CRAHNs

be exchanged among devices to broaden the knowledge on the network. The following are the main features of spectrum management functions.

Spectrum sensing: A CR user can be allocated to only an unused portion of the spectrum. Therefore, a CR user should monitor the available spectrum bands and then detect spectrum holes. Spectrum sensing is a basic functionality in CR networks and hence, it is closely related to other spectrum management functions as well as layering protocols to provide information on spectrum availability.

Spectrum decision: Once the available spectrums are identified, it is essential that the CR users select the most appropriate band according to their QoS requirements. It is important to characterize the spectrum band in terms of both radio environment and the statistical behaviours of the PUs. In order to design a decision algorithm that incorporates dynamic spectrum characteristics, we need to obtain a priori information regarding the PU activity.

Spectrum sharing: Since, there may be multiple CR users trying to access the spectrum, their transmissions should be coordinated to prevent collisions in overlapping portions of the spectrum. Spectrum sharing provides the capability to share the spectrum resource opportunistically with multiple CR users which includes resource allocation to avoid interference caused to the primary network. For this, game theoretical approaches have also been used to analyze the behaviour of selfish CR users. Furthermore, this function necessitates a CR Medium Access Control (MAC) protocol which facilitates the sensing control to distribute the sensing task among the coordinating nodes as well as spectrum access to determine the timing for transmission.

Spectrum mobility: If a PU is detected in the specific portion of the spectrum in use, CR users should vacate the spectrum immediately and continue their communications in another vacant portion of the spectrum. For this, either a new spectrum must be chosen or the affected links may be circumvented entirely. Thus, spectrum mobility necessitates a spectrum handoff scheme to detect the link failure and to switch the current transmission to a new route or a new spectrum band with minimum quality degradation. To overcome the drawback caused by the limited knowledge of the network all of spectrum management functions are based on cooperative operations where, CR users determine their actions based on the observed information exchanged with their neighbours.

COOPERATIVE COMMUNICATIONS

Cooperative communications and networking allows different users or nodes in a wireless network to share resources and to create collaboration through distributed transmission/processing in which each user's information is sent out not only by the user but also by the collaborating users. Cooperative communications and networking is a new communication paradigm that promises significant capacity and multi-plexing gain increase in wireless networks (Cover and El Gamal, 1979; Kramer *et al*., 2005). It also realizes a new form of space diversity to fight the injurious effects of severe fading (Laneman *et al*., 2004). There are mainly three relaying protocols: Amplify and Forward (AF), Decode and Forward (DF) and Compress and Forward (CF). In AF, the received signal is amplified and retransmitted to the destination. The advantage of this protocol is its simplicity and low cost implementation. But the noise is also amplified at the elay. In DF, the relay attempts to decode the received signals. If successful, it reencodes the information and retransmits it. Lastly, CF attempts to generate an estimate of the received signal. This is then compressed, encoded and transmitted in the hope that the estimated value may assist in decoding the original codeword at the destination.

COOPERATIVE SPECTRUM SENSING

The critical challenging issue in spectrum sensing is the hidden terminal problem which occurs when the CR is shadowed or in severe multi-path fading. Figure 6 shows that CR3 is shadowed by a high building over the sensing channel. In this case, the CR cannot sense the presence of the primary, user and thus, it is allowed to access the

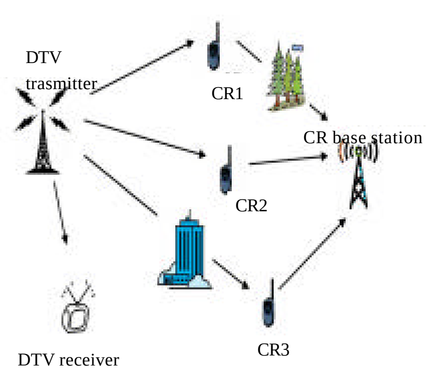

Fig. 6: Cooperative spectrum sensing in CR networks. CR 1 is shadowed over the reporting channel and CR 3 is shadowed over the sensing channel

channel while the PU is still in operation (Ben Letaief and Zhang, 2009). To address this issue, multiple CRs can be designed to collaborate in spectrum sensing (Cabric *et al.*, 2004). Recent research has shown that cooperative spectrum sensing can greatly increase the probability of detection in fading channels (Ghasemi and Sousa, 2005). Figure 7 shows the spectrum sensing structure in a cognitive radio network. In general, cooperative spectrum sensing can be performed as described below (Ben Letaief and Zhang, 2009):

Cooperative spectrum sensing:

- Every CR performs its own local spectrum sensing measurements independently and then makes a binary decision on whether the PU is present or not
- All of the CRs forward their decisions to a common receiver
- The common receiver fuses the CR decisions and makes a final decision to infer the absence or presence of the PU

Decision fusion vs. data fusion: The above cooperative spectrum sensing approach can be seen as a DF protocol for cooperative networks where each cooperative partner makes a binary decision based on the local observation and then forwards one bit of the decision to the common receiver.

At the common receiver, all 1-bit decisions are fused together according to an OR logic. We shall refer to this approach as decision fusion. An alternative form of cooperative spectrum sensing can be performed as follows. Instead of transmitting, the 1-bit decision to the common receiver in step 2 of the above algorithm each CR can just send its observation value directly to the common receiver (Visotsky *et al.*, 2005). This alternative approach can then be seen as an AF protocol for cooperative networks. We shall refer to this approach as data fusion. Obviously, the 1-bit decision needs a low bandwidth control channel.

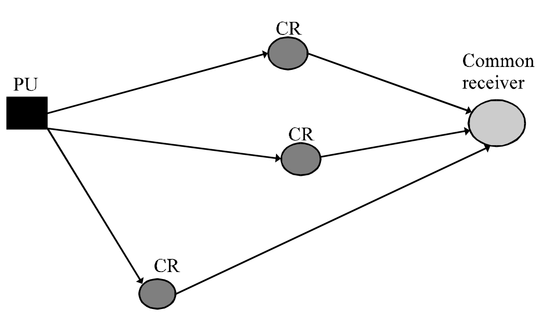

Fig. 7: Spectrum sensing structure in a cognitive radio network

Sensing diversity gain: It can be seen that cooperative spectrum sensing will go through two successive channels: sensing channel (from the PU to CRs) and reporting channel (from the CRs to the common receiver). The merit of cooperative spectrum sensing primarily lies in the achievable space diversity brought by the sensing channels, namely, sensing diversity gain, provided by the multiple CRs.

Even though, one CR may fail to detect the signal of the PU, there are still many chances for other CRs to detect it. With the increase of the number of cooperative CRs, the probability of missed detection for all the users will be extremely small. Another merit of cooperative spectrum sensing is the mutual benefit brought forward by communicating with each other to improve the sensing performance (Ghurumuruhan and Li, 2005).

When one CR is far away from the primary user, the received signal may be too weak to be detected. However by employing a CR that is located nearby the PU as a relay, the signal of the PU can be detected reliably by the far user. The following is a simulation result shown based on cooperative gain and the number of users. Cooperative sensing is characterized by cooperative gain as shown in Fig. 8.

This is defined as the improvement in probability of detection/false alarm due to cooperation. The plot shows the cooperative gain resulting from cooperative spectrum sensing with increasing number of users. Limitation of cooperative spectrum sensing is that in practice, the reporting channels between the CRs and the common receiver will also experience fading and shadowing (Fig. 5). This will typically deteriorate the transmission reliability of the sensing results reported from the CRs to the common receiver. For example when one CR reports a sensing result {1} (denoting the presence of the PU) to

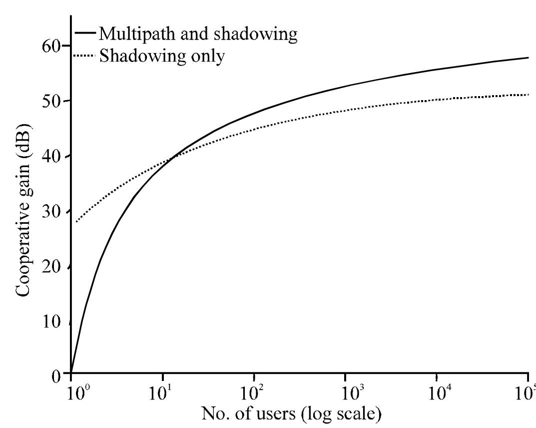

Fig. 8: Cooperative sensing characterized by cooperative gain

the common receiver through a realistic fading channel, the common receiver will likely detect it to be the opposite result {0} (denoting the absence of the PU) because of the disturbance from the random complex channel coefficient and random noise. Eventually, the performance of cooperative spectrum sensing will be degraded by the imperfect reporting channels.

COOPERATIVE SPECTRUM SHARING

CR has the ability to dynamically adapt to the local spectrum environment. Due to the dispersed geographic locations of the secondary devices in a CR network, each CR may experience diverse spectrum conditions such as the activities of different PUs. In Fig. 9 such a CR network with various scenarios is depicted. As we can see, CR1 is within the transmission range of PU1 (i.e., the cognitive radio can sense the signal transmitted from the PU1) while CR2 is located in the transmission range of PU2. Since, the two PUs may operate independently over a wide-band spectrum, it is most likely that some portions of the spectrum may not be utilized by the primary systems over some time.

As such, CRs 1 and 2 can detect various spectrum holes of PUs 1 and 2, respectively. For instance in a given period, the available frequency bands for CR 1 are f1 and f2 while for CR 2 they are f2 and 3. Note that the number of available channels and channel identities vary from one CR to another within the network. This in turn results in a wealth of spectrum opportunities that the CR network can dynamically exploit to support continuous transmission, regardless of whether one of the PUs reuses some of the channels or not.

Cognitive relay network: Ben Letaief and Zhang (2009) considered a cognitive wireless relay network consisting of a source node that intends to communicate with a destination node aided by a total number of K relay nodes and assumed that each cognitive relay node is within the transmission range of one PU node. It is also assumed that >1 CR node can share the radio spectrum within one PU operating range when the PU is inactive. Furthermore, assumed that each PU operates in a wide-band channel consisting of a number of non-overlapping frequency bands f1, f2, . ., fN, where N denotes the total number of frequency bands in the bandwidth of Pus (Ben Letaief and Zhang, 2009).

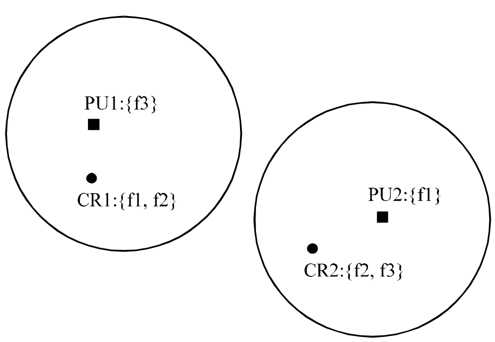

Fig. 9: Example of cognitive wireless network. CR1 is within transmission range of PU1 and CR2 is in the range of PU2. The two PUs are in operation independently

Each cognitive relay first gets the spectrum map of its local channel environment by spectrum sensing. The number of available bands varies from one relay to another in cognitive relay networks. One of the benefits of the cognitive relay network is that seamless transmission can be realized. Without cognitive relay, the source node (cognitive user) will send data to the destination node directly when the source-destination channel is not utilized by the PUs. If the PU returns over to the channel, the source should stop its transmission immediately so as not to cause interference to the primary system.

Aided by a large number of cognitive relays, the transmission in the cognitive relay network does not necessarily stop even when some PUs are operating again. This is because there is always at least one available band in the cognitive relays that can be utilized as a relay channel to continue data transmission. Resource allocation is a fundamental problem in cognitive radio networks and has been discussed a lot in the existing researches (Yuan *et al*., 2007; Ma *et al*., 2005; Chen *et al*., 2008; Jia *et al*., 2008).

However when the traffic demand and spectrum resource availability are largely mismatched, existing researches cannot fully utilize spectrum resource and fulfill secondary users' demands. Thus, an important issue is how to handle the unbalanced spectrum usage within the secondary network to fulfill the heterogeneous traffic demand from secondary users (Zhang *et al*., 2009; Jia *et al*., 2009).

It is observed that some secondary users do not need to use their entire available spectrum because of the low traffic demand. If we can utilize these rich nodes as helpers to relay the other secondary user's traffic with their otherwise wasted spectrum we can improve the system performance.

Cognitive transmissions with multiple relays: CR users in a CR ad-hoc network can communicate with each other in a multi-hop manner. Reasons to use the relaying concept in CR ad-hoc network are:

- To enhance or maintain the data quality. Since, data travelling over a long distance is subjected to degradation, use relay nodes to transmit data without degradation
- To provide correctness of data. Consider two paths are available to transmit a message from source to destination where one is a direct path and another is an indirect path. If the direct path is prone to change the content of the message and not the indirect path then the indirect path is selected to transmit the message using relaying is preferred

In traditional (non-cognitive radio) multiple-relay networks, three relay protocols (i.e., fixed relaying, selection relaying and incremental relaying) have been studied extensively (Laneman *et al*., 2004; Zou *et al*., 2010). It is observed that the advantages of such relaying protocols are achieved at the cost of a reduction in spectral efficiency since, the relays used transmit on orthogonal channels to avoid interfering each other. To address the shortcoming of an inefficient utilization of the spectrum resource, a best-relay selection protocol has been investigated by Bletsas *et al.* (2006), Beres and Adve (2008) where only the best relay is selected to forward a source node's signal and thus only two channels (i.e., the best relay link and direct link) are required regardless of the number of relays. It has been shown by Bletsas *et al.* (2006) that the best-relay selection scheme can achieve the same diversity multi-plexing tradeoff performance as the traditional protocols where all relays are involved in forwarding the source node's signal. Accordingly, the best-relay selection is also an attractive relay protocol for cognitive radio networks due to its spectrum efficiency. However, compared with the best-relay transmission in traditional wireless networks, cognitive radio networks has the mutual interference between the primary and the cognitive users as a challenging issue for consideration, especially in a relay network scenario. Thus, sensing accuracy is very important for avoiding the interference caused to the primary users. The accuracy can be increased by cooperative sensing considering both spectrum efficiency and interference avoidance.

CONCLUSION

CR networks are envisaged to solve the problem of spectrum scarcity by making efficient and opportunistic use of frequencies reserved for the use of licensed users of the bands. To realize the goals of truly ubiquitous spectrum-aware communication, the CR devices need to incorporate the spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility functionalities. Cooperative communications can play a key role in the development of CR networks. In this study, we have presented an overview of the cooperative spectrum sensing and cooperative spectrum sharing. Relays eliminate the hidden terminal problem.

Also, the dynamic spectrum can be fully utilized through a number of cognitive relay nodes that can support seamless data service for cognitive users. Though, the best-relay selection is an attractive relay protocol for cognitive radio networks due to its spectrum efficiency compared with the best-relay transmission in traditional wireless networks, cognitive radio networks face an additional challenging issue, i.e., mutual interference between the primary and the cognitive users, especially in a relay network scenario.

REFERENCES

Akyildiz, I.F., W.Y. Lee, M.C. Vuran and S. Mohanty, 2006. NeXt generation dynamic spectrum access cognitive radio wireless networks: A survey. Comput. Networks J., 50: 2127-2159.

Akyildiz, I.F., W.Y. Lee and K.R. Chowdhury, 2009. CRAHNs: Cognitive radio ad hoc networks. Ad Hoc Networks, 7: 810-836.

Basar, T. and G.J. Olsder, 1999. Dynamic Noncooperative Game Theory. 2nd Edn., SIAM Publication, Philadelphia, PA., USA.

Ben Letaief, K. and W. Zhang, 2009. Cooperative communications for cognitive radio networks. Proc. IEEE, 97: 878-893.

Beres, E. and R. Adve, 2008. Selection cooperation in multi-source cooperative networks. IEEE Trans. Wireless Commun., 7: 118-127.

Bletsas, A., A. Khisti, D.P. Reed and A. Lippman, 2006. A simple cooperative diversity method based on network path selection. Select. Areas Commun. IEEE J., 24: 659-672.

Cabric, D., S.M. Mishra and R.W. Brodersen, 2004. Implementation issues in spectrum sensing for cognitive radios. Proc. Asilomar Conf. Signals Syst. Comput., 1: 772-776.

Chen, D., Q. Zhang and W. Jia, 2008. Aggregation aware spectrum assignment in cognitive Ad-hoc networks. Proceedings of the 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, May 15-17, CrownCom, Singapore, pp: 1-6.

Compton, R.T., 1988. Adaptive Antennas: Concepts and Performance. Prentice-Hall, Englewood Cliffs, New Jersey..

Cover, T.M. and A.A. El Gamal, 1979. Capacity theorems for the relay channel. IEEE Trans. Inf. Theory, 25: 572-584.

Ghasemi, A. and E.S. Sousa, 2005. Collaborative spectrum sensing for opportunistic access in fading environments. Proceedings of the 1st IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, Nov. 8-11, Baltimore, USA., pp: 131-136.

Ghurumuruhan, G. and Y. Li, 2005. Agility improvement through cooperative diversity in cognitive radio. IEEE Global Telecommun. Conf., 5: 2509-2509.

Haykin, S., 2005. Cognitive radio: Brain-empowered wireless communications. IEEE JSAC, 23: 201-220.

Jia, J., Q. Zhang and X. Shen, 2008. HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management. IEEE J. Selected Areas. Commun., 26: 106-117.

Jia, J., J. Zhang and Q. Zhang, 2009. Cooperative relay for cognitive radio networks. Proceedings of the IEEE INFOCOM, April 19-25, Rio de Janeiro, Brazil, pp: 2304-2312.

Kramer, G., M. Gastpar and P. Gupta, 2005. Cooperative strategies and capacity theorems for relay networks. IEEE Trans. Inf. Theory, 51: 3037-3063.

Laneman, J.N., N.C.T. David and G.W. Wornell, 2004. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. IEEE Trans. Inform. Theory, 50: 3062-3080.

Ma, L., X. Han and C.C. Shen, 2005. Dynamic open spectrum sharing MAC protocol for wireless ad hoc networks. Proceedings of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Nov. 8-11, Baltimore, MD., USA., pp: 203-213.

McHenry, M., 2003. Frequency agile spectrum access technologies. FCC Workshop on Cognitive Radios, May 19.

Ralston, A. and E. D. Reilly, 1993. Encyclopedia of Computer Science. Van Nostrand, New York, pp: 186-186.

Staple, G. and K. Werbach, 2004. The end of spectrum scarcity. IEEE Spectr., 41: 48-52.

Visotsky, E., S. Kuffner and R. Peterson, 2005. On collaborative detection of TV transmissions in support of dynamic spectrum sensing. Proceedings of the 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, Nov. 8-11, Baltimore, MD., USA., pp: 338-345.

Welch, P.D., 1967. The use of fast Fourier transform for the estimation of power spectra: A method based on time-averaging over short, modified periodograms. IEEE Trans. Audio Electroacoust., 15: 70-73.

Yuan, Y., P. Bahl, R. Chandra, P. Chou and J. Ferrell *et al*., 2007. KNOWS: Kognitiv networking over white spaces. Proceedings of the IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, (DySPAN'07), Dublin, Ireland, pp: 416-427.

Zhang, Q., J. Jia and J. Zhang, 2009. Cooperative relay to improve diversity in cognitive radio networks. IEEE Commun. Mag., 47: 111-117.

Zou, Y., Y. Yao and B. Zheng, 2010. Cognitive transmissions with multiple relays in cognitive radio networks. IEEE Trans. Wireless Commun., 10: 648-659.