Cognitive Radio Simplex Link Management for Dynamic Spectrum Access Using GNU Radio

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Abstract The explosion of new wireless communication technologies and services has led to the increase in spectrum demand. The fixed spectrum allocation approach has resulted in current day spectrum scarcity and poorly utilized licensed spectrum. In order to overcome these problems, a new concept of accessing the spectrum, defined as dynamic spectrum access (DSA), is proposed. DSA mechanism enables unlicensed or cognitive users (CUs) to temporarily utilize a spectrum hole for a period of time. In this work, DSA based on cognitive radio (CR) technology is chosen due to its features of able to sense, learn, adapt and react according to the environment. The proposed design of the system consists of four main functional blocks: spectrum sensing, spectrum management, spectrum

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decision and data transmission. Spectrum management is further divided into three parts: spectrum identification, synchronization and link management. This paper focuses on the establishment of link management module in simplex mode. The implementation is done using GNU Radio and USRP SDR platform. The GMSK based and IEEE 802.15.4 standard radios, equipped with DSA capability using CR technique, have been developed and tested. The results show that the link module has successfully maintained CU's seamless communication while the DSA mechanism offers significant improvement in terms of achieved packet rate ratio (PRR).

Keywords Dynamic spectrum access · Cognitive radio · Spectrum sensing · Spectrum management and spectrum decision

1 Introduction

There has been tremendous demand for radio spectrum recently due to emerging of new wireless communication technologies and services such as long term evolution (LTE) and LTE-advanced. Traditional static spectrum allocation policies as practiced in many countries including Malaysia has resulted in spectrum scarcity as most radio bands are already assigned to users by the regulators. However, a number of spectrum occupancy measurements [1–4] has shown that the licensed spectrum is poorly utilized where some bands are overcrowded while other portions are moderately or rarely utilized as shown in Fig. 1. Cognitive radio (CR) is a promising technology to provide highly reliable communication for all users in the network wherever and whenever needed and to facilitate efficient spectrum utilization. It promotes spectrum sharing approach where unlicensed or cognitive users (CUs) are allowed access to licensed channel as long as there is no interference to licensed or primary users' (PUs) transmission.

There are two basic approaches of spectrum sharing which are the underlay and overlay. Underlay approach allows CUs to simultaneously share the spectrum with licensed user but the transmission of information is strictly limited to be below the designated threshold [5, 6]. In contrast, the overlay spectrum sharing prohibits CUs to simultaneously use the same frequency which is in use by PUs. Hence, CUs have to robustly identify a spectrum opportunity (spectrum hole).

Dynamic spectrum access (DSA) is an enabling technology for overlay spectrum sharing. IEEE 1900.1 working group defined DSA as a technique which enable a radio to dynamically change its operating frequency in real-time based on the condition of the environment and the objectives of the system [7, 8]. With DSA, CUs can temporarily utilize unoccupied bands but need to be sufficiently agile to vacate the space (time, frequency or spatial) once PUs are detected as not to cause harmful interference [5–8].

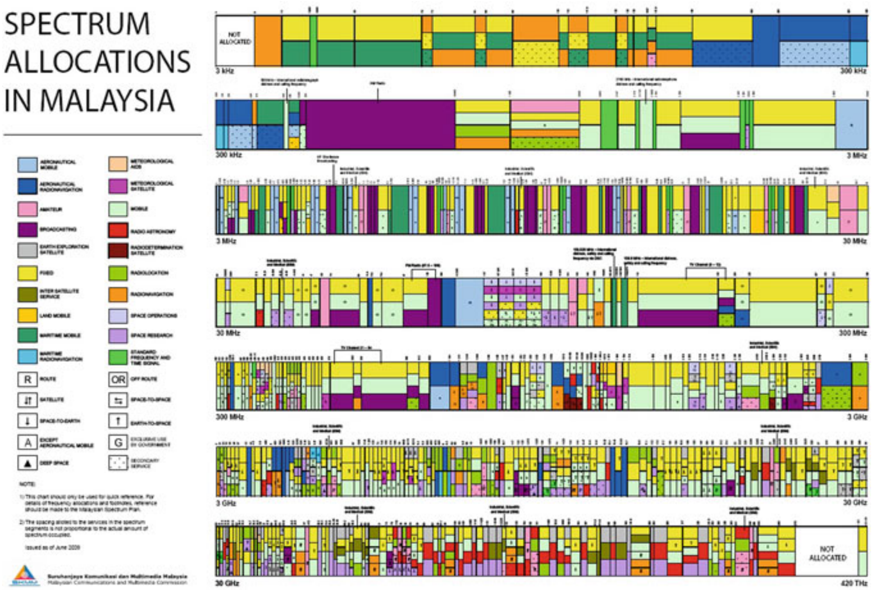

Fig. 1 Local spectrum utilization [1]

DSA can be realized through a number of available technologies, which include adaptive radio [9], cognitive radio (CR) [10], and reconfigurable radio [11, 12]. The most appropriate means to realize these radios are through the use of several existing software defined radio (SDR) platforms in the market [13–19]. A working prototype of DSA hardware implementation using GNU radio and USRP is presented in [20]. The work utilizes energy detector as its sensing method. Synchronization between two communicating CUs is established using simplex mode. A CU transmitter senses the channel to determine its status before the packet is transmitted. Each time it changes channel, CU transmitter will broadcast a number of synchronization packets on the found free channel. By sweeping channel and detecting the transmitted synchronization packet, the channel used by CU transmitter will be known by CU receiver.

In the work presented here, a similar DSA based CR system is developed using universal software radio peripheral (USRP) and GNU radio as hardware and software platforms, respectively. The proposed design consists of four main functional blocks which are spectrum sensing, spectrum management, spectrum decision and data transmission. However, the process of establishing communication between two CUs is further enhanced and made more effective by having a link management module, integrated with spectrum identification and synchronization as parts of spectrum management. This module is in simplex mode and is responsible for spectrum mobility where seamless communication requirements for CUs are maintained during the transition to better spectrum. An open platform technology is also utilized to facilitate flexible modification according to users' requirement and specification.

The rest of the paper is organized as follows. Section 2 presents the design concept of DSA based CR system. The details of Link Management module is explained in Sect. 3. The CR network model is introduced in Sect. 4 while Sect. 5 discusses the implementation set-up and the results. The conclusion of this paper is outlined in Sect. 6.

2 Design Concept of CR System for DSA

The proposed design of the CU system with DSA is illustrated by the block diagram in Fig. 2. It consists of four main functioning blocks: spectrum sensing, spectrum management, spectrum decision and data transmission. Spectrum sensing is used to sense the spectrum and detects the presence of the PU on the scanned spectrum. Spectrum management is responsible for identifying the spectrum hole (spectrum hole identification), establishing synchronization and managing links with other CUs or secondary users (SUs).

Spectrum decision is responsible for summarizing the output from spectrum management which is the availability of the spectrum hole, the status of the synchronization and the status of the link and make decision on when and how to communicate, for instance the use and how long the channel can be utilized. Last but not least, the data transmission which functions is to forward data packets to the USRP (i.e. assemble and transmit the data). This paper highlights the work on link management in spectrum management module. More details on the operation of the CU can be found in [21].

3 Link Management

Link management resides in spectrum management module in the designed CR system. It is responsible for keeping seamless communication between CUs even when it changes its physical parameter such as the channel identification (id) used or spectrum band. In this work, the link management is in simplex mode. However, it can be easily extended to duplex mode as the system is built on open platform. The design of link management considers that the control packet has been successfully carried out.

The link management process begins after CU senses the spectrum hole. As shown in Fig. 3, once spectrum hole is found, CU transmitter will initiate synchronization and connection id with the corresponding CU receiver by sending the control packet using the default channel (channel 20 as in Table 1). This is to ensure the corresponding CU has been informed that communication between both parties will begin or resume using the identified channel. Channel 20 is chosen as the default channel as it does not interfere with the neighboring access point.

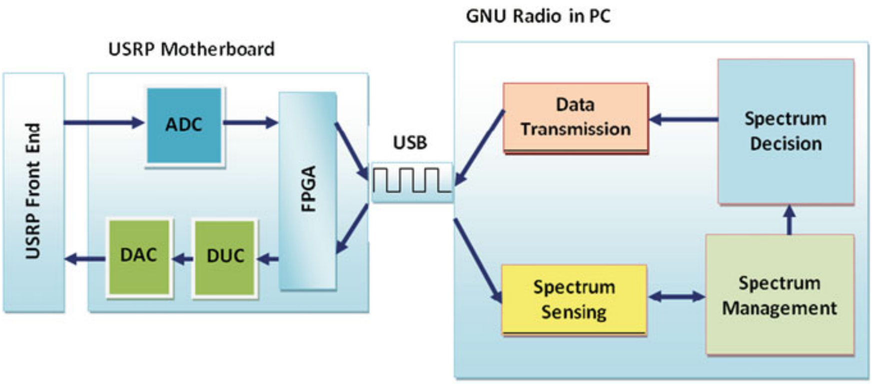

Fig. 2 Design concept of CR system for DSA

Fig. 3 Link management in CU system

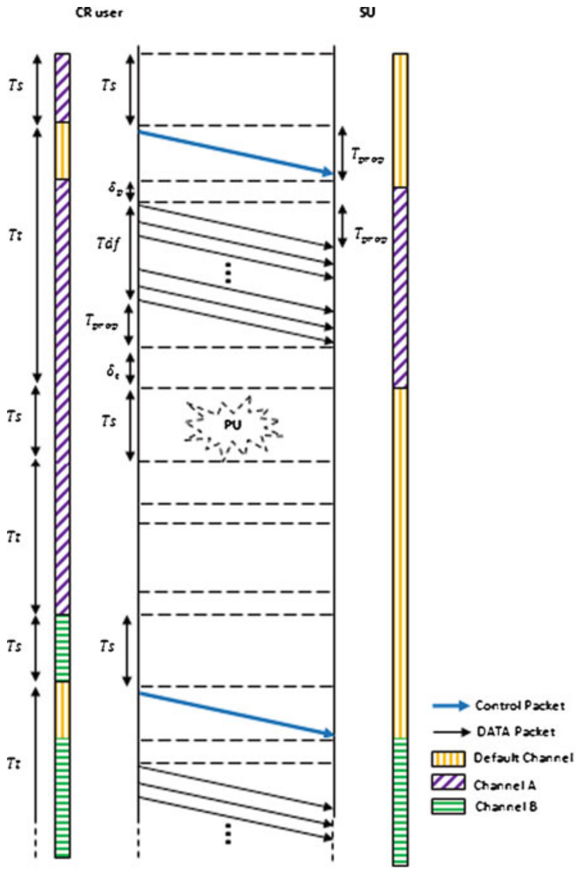

Table 1 Channel and frequency used in CR system [20]

Channel	Frequency (GHz)
1	2.404
2	2.408
3	2.412
4	2.416
5	2.420
6	2.424
7	2.428
8	2.432
9	2.436
10	2.440
11	2.444
12	2.448
13	2.452
14	2.456
15	2.460
16	2.464
17	2.468
18	2.472
19	2.476
20	2.480
21	2.484
22	2.488
23	2.492
24	2.496

The same process for sending data is repeated for the next time frame using the next identified spectrum hole as shown in Fig. 3.

In this figure, T_s is the sensing time equal to 31.59 ms. T_{prop} is the signal propagation delay as given in Eq. 1;

$$T_{prop} = \frac{d}{v} \tag{1}$$

where d is the distance between the transmitter and the receiver which in this case is equal to 0.66 m, and v is the speed of the speed of the light (300×10^6 m/s). Thus T_{prop} is equal to 2.2 ns. Tdf is the data packet transmission time and can be derived using Eq. 2,

$$Tdf = Tpx\ (No.\, of\ Packets) \tag{2}$$

$$Tp = \frac{F_s}{L} \tag{3}$$

where F_s is the frame size, L is the link rate and Tp is the time needed to transmit a packet of data and can be calculated using Eq. 3. The frame size in GMSK based radio is 2 packet/frame and Tp is equal to 65.744 ms. Therefore Tdf is equal to

131.488 ms. δ_p is offset which is needed by the CU receiver to stabilize after changing to a new channel or spectrum band. Since USRP is used in this study and its response on the channel and spectrum band changes is very fast, therefore δ_p is set to zero. δ_t is the remaining time until the next frame and can be calculated using Eq. 4;

$$\delta_t = Tt - Tdf \tag{4}$$

In this work, Tt is equal to 192.25 ms. Therefore, δ_t is equal to 60.762 ms. The utilization of the link can be calculated using the following equation:

$$U = \frac{Tdf}{Ts + 2T_{prop} + \delta_p + Tdf + \delta_t} \tag{5}$$

Putting all the value in the equation gives U equal to 0.6839. The dominant parameters which degrade the utilization of the CR system is Ts and δ_t. The utilization can be improved by minimizing Ts and δ_t and it can be done as follow:

- Using faster and more powerful computer to execute the GNU Radio as this will speed up the processing of the signal processing block of the GNU Radio.
- Using joint sensing and data transmission as proposed in [22]. This technique is better if it is used with USRP2 which provides better bandwidth to exchange the data from SDR hardware to the GNU Radio.
- Choosing a lower sensing time for the CR system. However, this will degrade the Pd and Pfa.

4 CR Network Model

Figure 4 illustrates the CR network model used in this work. In this figure, PU and CU radios are operating in the same frequency band which in this work is at 2.4 GHz ISM band. The frequency started at 2.404 GHz which is channel 1 and end at 2.496 GHz which is channel 24. CU is assumed to operate in the PU coverage area.

4.1 CU Characteristics

Table 2 shows the parameters used by CU in this work. There are two types of CU radio system tested which are the GMSK based radio and IEEE 802.15.4 standard radio. Both radios operates in ISM 2.4 GHz band. The link rate of GMSK based radio is 500 kb/s and the bandwidth is 1 MHz. The maximum payload size of the radio is 4085 bytes which is limited by the maximum value of packet length in MAC header. The length can be increased by adding the size of the packet length

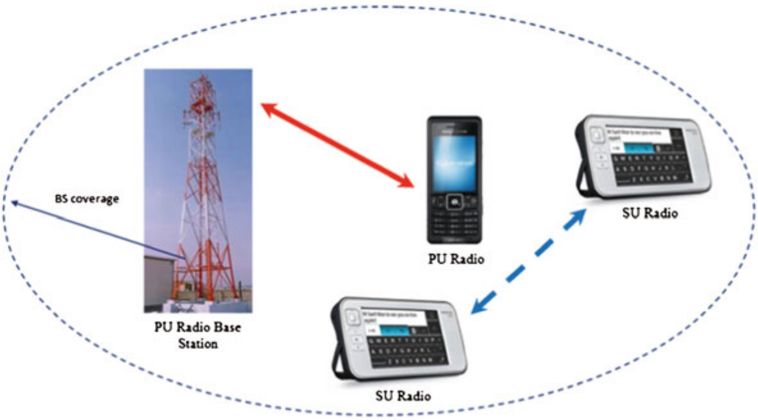

Fig. 4 CR network model

Table 2 Parameters used for SU radio

Parameter	GMSK based	IEEE 802.15.4 standard
Modulation	GMSK	O-QPSK
Bitrate	500 kb/s	256 kb/s
Band	2.4GHzISM Band	2.4GHz ISM Band
Bandwidth	1 MHz	3 MHz
Max. payload size	4085 bytes	128 bytes
MTU	4108 bytes	156 bytes

in the PHY header. The maximum transfer unit (MTU) for the GMSK based radio is 4108 bytes. For IEEE 802.15.4, the link rate is 256 kb/s with the bandwidth of 3 MHz. The modulation used in this radio is offset quadrature phase shift keying (O-QPSK) and the maximum packet length allowed is 128bytes and the MTU is 156 bytes.

4.2 *PU Characteristics*

The parameters used for the PU radio in this work are listed in Table 3. PU is operating in the same band as CU which is the ISM 2.4 GHz. This is to prove that PU and CU can share the same band. The bitrate of this radio is 500 kb/s with 1 MHz bandwidth. The modulation used for PU radio in this work is the differential phase shift keying (DQPSK) and the packet size transmitted is 1500 bytes. PU on and off time is based on work in [23] which is 352 and 650 ms, respectively. PU packet is generated every 30 ms within the on time.

Table 3 Parameters used for PU radio

Parameter	PU Radio
Modulation	DQPSK
Bitrate	500 kb/s
Band	2.4GHz ISM Band
Bandwidth	1 MHz
Pkt Size	1500 bytes

5 Implementation Setup

In the implementation of the CR system, four USRPs, one laptop and one personal computer (PC) were used as shown in Fig. 5. PC with USRP A acts as the CU receiver, PC with USRP B as the monitoring node (the spectrum analyzer), laptop and USRP C as the CU transmitter and laptop with USRP D acts as the PU transmitter. Daughter board used for this implementation is RFX2400 which covers frequencies from 2.3–2.9 GHz. In this implementation, only two channels are used as prove of concept purposes. The channels are channel 22 (2.488 GHz) as channel A and channel 23 (2.492 GHz) as channel B. These channels are considered since they do not overlap with the neighboring access points (WLAN) which can interfere with the USRP frequency operating at 2.4 GHz band.

5.1 Results of CR Network Implementation on GMSK Based Radio

The graphical results of the GMSK based CR network implementation are presented in Fig. 6a–d. In Fig. 6a, it is observed that PU and CR transmitters are transmitting at different channel frequencies in the same band; the signal with lower amplitude transmitting at 2.492 GHz is the CU signal with GMSK modulation while the higher one transmitting at 2.488 GHz is the PU signal with DQPSK modulation.

When PU appears on the channel where the CU is currently transmitting as shown in Fig. 6b, CU will stop its transmission as shown in Fig. 6c. CU will search for another free channel. Once the free channel is identified, CU will continue its communication by using this new free channel or spectrum hole as shown in the picture in Fig. 6d.

It is crucial for CU to change the channel frequency used not only to give the PU privilege of using the channel but also to protect it from interference. Figure 4 shows that the effect of interference on CU's packet reception rate for GMSK based radio. As shown in Fig. 7, with only 50% power transmission by PU, the packet reception rate (PRR) of CU drops to 0.084, a reduction of 91.6% from the original value.

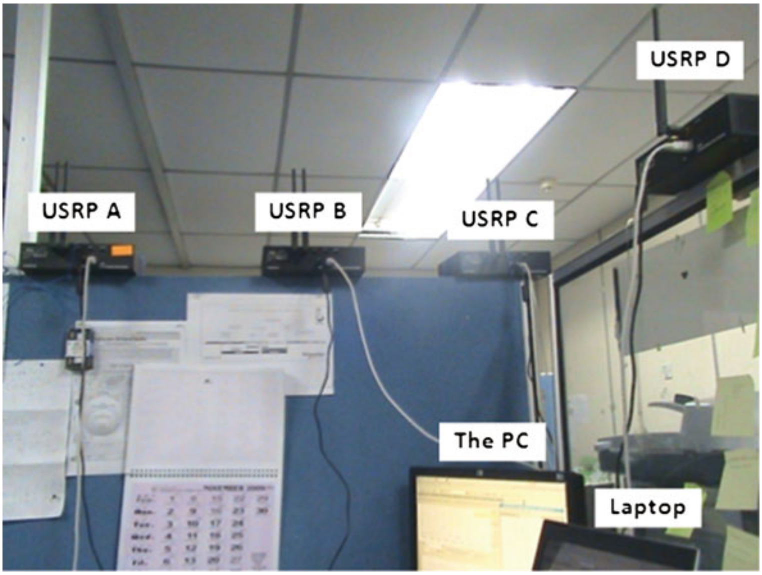

Fig. 5 Experimental setup of CR system implementation

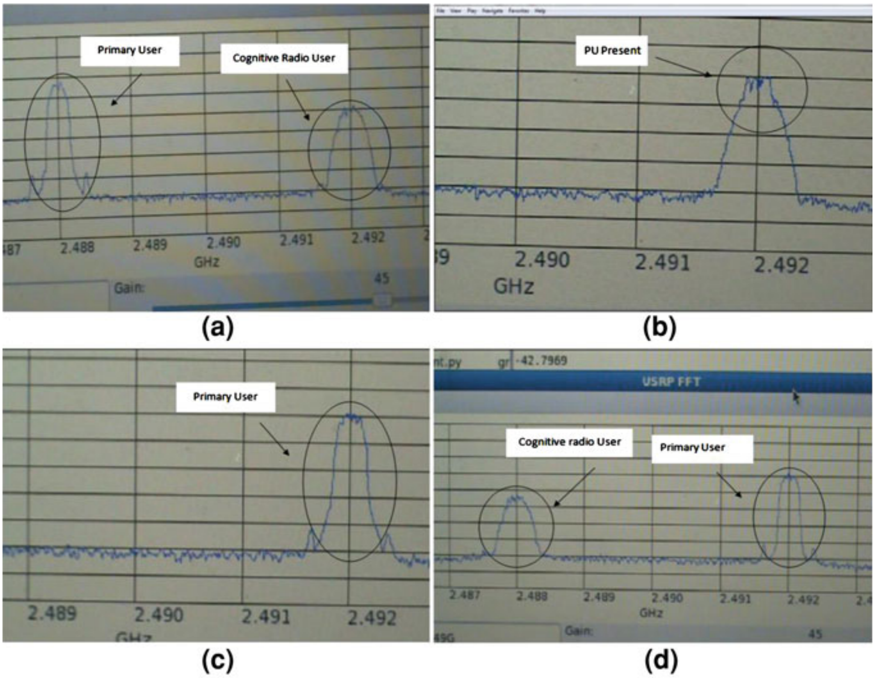

Fig. 6 **a** Overlay spectrum sharing between PU and CU **b** Detection of PU in the channel occupied previously by CU **c** CU stops transmission **d** CU finds another spectrum hole and resumes transmission

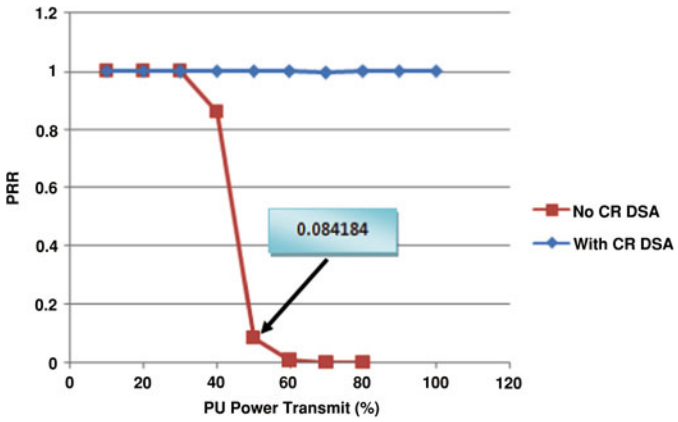

Fig. 7 PRR for GMSK based radio with and without CR system

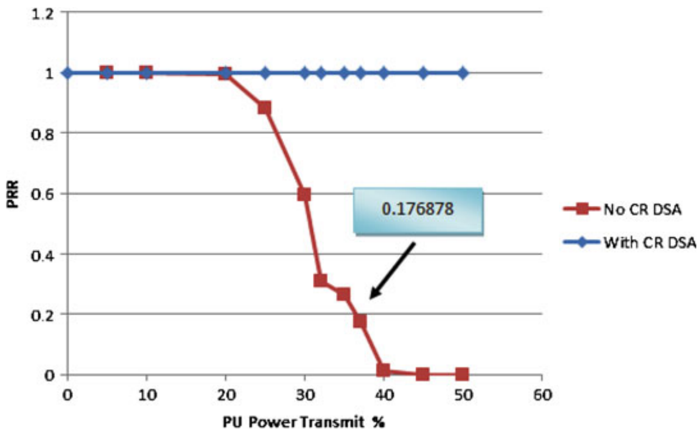

Fig. 8 PRR for IEEE 802.15.4 standard radio with and without DSA based CR system

5.2 Results of CR Network Implementation on IEEE 802.15.4 Standard Radio

Similarly for the IEEE 802.15.4 standard radio, the graph in Fig. 8 shows that the DSA based CR system improves the PRR of CU significantly. IEEE 802.15.4 standard radio without DSA mechanism suffers from the interference caused by the PU badly. As shown in this graph with only 37% power transmits used by the PU, CU's PRR dropped to 0.176, which is a reduction by 82.6%. However, for the IEEE 802.15.4 radio which is equipped with DSA capability, the PRR value is maintained at around 1.0 even though PU transmits at 100% power.

6 Conclusion

The complete CR system for DSA which consists of spectrum sensing, spectrum management and spectrum decision has been implemented and tested. The working link management module which is part of the spectrum management is also successfully developed and implemented. The calculation shows that the minimum link utilization of the work is 68% and this can be improved by reducing the sensing time.

Furthermore, CU system deploying proposed DSA is shown to significantly improve the spectrum utilization in terms of packet reception rate for both GMSK based and IEEE 802.15.4 standard radios. Future works include the implementation of the link management in duplex mode and more measurements to evaluate the performance of the developed system.

References

1. Suruhanjaya Komunikasi dan Multimedia Malaysia (SKMM) (2010) Spectrum allocation in Malaysia. http://www.skmm.gov.my/link_file/what_we_do/spectrum/allocation/pdf/Malaysian_Spectrum_Allocations_Chart.pdf. Accessed on Oct 29
2. McHenry MA, Tenhula PA, McCloskey D, Roberson DA, Hood CS (2006) Chicago spectrum occupancy measurements & analysis and a long-term studies proposal. In: Proceedings of the first international workshop on technology and policy for accessing spectrum. Boston, MA, 5 Aug 2006
3. Cabric D, Mishra SM, Brodersen RW (2004) Implementation issues in spectrum sensing for cognitive radios. In: Asilomar conference on signals, systems, and computers. vol 1. pp 772–776, Nov 2004
4. Akyildiz IF, Lee W-Y, Vuran MC, Mohanty S (2006) Next generation dynamic spectrum access cognitive radio wireless networks: a survey. Int J ComputTelecommun Network 50:2127–2159
5. Berlemann L, Dimitrakopoulos G, Moessner K, Hoffmeyer J (2005) Cognitive radio, Management of spectrum and radio resources in reconfigurable networks. In: Wireless world research forum working group 6 White Paper
6. Rashid RA, Fisal N (2009) Issues of spectrum sensing in cognitive radio based system. In: Third south east asia technical universities consortium (SEATUC), Johor, Malaysia, 25–26 Feb 2009
7. International telecommunication union (ITU) (2002) Handbook frequency-adaptive communication systems and networks in the MF/HF bands
8. Mitola III J (2000) Cognitive radio: an integrated agent architecture for software defined radio. Ph.D. thesis, KTH- Royal institute of technology, Stockholm, Sweden
9. International telecommunication union (ITU) (2002) Handbook frequency-adaptive communication systems and networks in the MF/HF bands
10. Mitola III J (2000) Cognitive radio: an integrated agent architecture for software defined radio. Ph.D. thesis, KTH-Royal institute of technology, Stockholm, Sweden
11. Guenin J (2008) IEEE SCC41 standards for dynamic spectrum access networks. In: IEICE software and cognitive radio expo and technical conference. Tokyo, Japan, 1 Aug 2008
12. Hamid M (2008) Dynamic spectrum access in cognitive radio networks: Aspects of mac layer sensing. Master Thesis, Blekinge Institute of Technology, Ronneby, Sweden, Dec 2008

13. Baldiniet G et al (2008) Reconfigurable radio systems for public safety based on low-cost platforms. EuroISI 2008, LNCS vol 5376. pp 237–247
14. IEEE communications society (2008) 1900.1-2008 IEEE standard definitions and concepts for dynamic spectrum access: terminology relating to emerging wireless networks, System functionality, and spectrum management. 26 Sept 2008. pp c1–48. E-ISBN 978-0-7381-5776-4, Printed ISBN 978-0-7381-5777-1
15. Mitola III J (1992) Software radios-survey, critical evaluation and future directions. IEEE National telesystems conference. Washington, DC, May 1992, pp 19–20, 13/15–13/23
16. Mitola J (2002) The software radio architecture. IEEE Commun Mag 33(5):26–38
17. Flex radio systems (2010) http://www.flex-radio.com/. Accessed 2 Nov 2010
18. Berkeley emulation engine (2010) 2. http://bee2.eecs.berkeley.edu/. Accessed 2 Nov 2010
19. GNU radio (2010) http://gnuradio.org. Accessed 2 Nov 2010
20. Alice Crohas (2008) Practical implementation of a cognitive radio system for dynamic spectrum access. Master of science in electrical engineering thesis. Notre Dame, Indiana, July 2008
21. Adib Sarijari M, Rashid RA, Fisal N, Lo ACC, Yusof SKS, Mahalin NH (2011) Dynamic spectrum access using cognitive radio utilizing GNU radio and USRP. 26th wireless world research forum (WWRF26) Doha, Qatar, 11–14 Apr 2011
22. Do T, Mark BL (2009) Joint spatial-temporal spectrum sensing for cognitive radio networks. In: Proceedings of conference on information sciences and systems (CISS 09) Baltimore, MD, Mar 2009
23. Pei Y, Hoang AT, Liang Y-C (2007) Sensing-throughput tradeoff in cognitive radio networks: how frequently should spectrum sensing be carried out? IEEE 18th international symposium on personal, indoor and mobile radio communications. PIMRC 2007, Athens, pp 1–5, 3–7 Sept 2007