

On the Throughput Improvement of Cognitive Radio Networks

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Abstract- The under-utilization of the scarce spectrum triggered the need for opportunistic spectrum sharing among mobile radio users recently. Cognitive radio (CR) is considered as a promising candidate to be employed in such systems as they are aware of their operating environments and can be trained to dynamically and autonomously adjust its radio operating parameters accordingly. The capability of the cognitive radio to sense, learn, and adapt to the radio environment provides new opportunities for spectrum users. The objective of this study is to design and analyze a more reliable cognitive radio network that is able to establish a virtual wireless link before the actual communication starts. In spectrum detection schemes, the secondary user will be allocated a channel if and only if there is free accessible channel in the primary users' band. In this paper we design a system model for the cognitive radio network and develop a virtual wireless link selection (VWLS) algorithm for cognitive radio networks. The VWLS algorithm is then analyzed and computer simulated to show the impact of the virtual link on the throughput of the network. By demonstrating the throughput improvement of the cognitive radio network (CRN) with the help of the newly developed algorithm, we can prove that the reliability can also be enhanced.

Index Terms- cognitive radio, cognitive radio network, spectrum sensing, virtual wireless link selection algorithm.

I. INTRODUCTION

RADIO wave frequency bands in accordance with Article 5 of the ITU Radio regulations range from 9 kHz to 275GHz. EM waves with frequencies less than 9 KHz are not employed due to the following reasons: i) Limited bandwidth resulting in low traffic capacity and ii) Very large antennas because of long wavelengths [1]-[3]. Also, frequency bands higher than 100GHz are not usually employed for the time being due to the following reasons: High free space loss, High atmospheric attenuation and Limitations in radio frequency (RF) component manufacturing [1], [3]. The fixed spectrum assignment scheme is confronting difficulties due to the scarcity of the natural usable radio frequency band we have [3]-[5]. To mitigate the spectrum scarcity problem different techniques have been proposed so far in the literature, among which, the CR technology is the main one. CRs allow a Secondary User (SU) to dynamically access portions of the radio spectrum that lie fallow at a particular time and location by the license-holder also known as the Primary User (PU)

without causing any harmful interference [7], [9]-[13]. According to, Haykin [8], CR selects the communication parameters such as modulation, coding, carrier frequency, channel bandwidth and transmission power to optimize the spectrum usage and adapts its transmission and reception accordingly.

In cognitive radio networks, uncertainties in received signal strength arise due to channel fading or shadowing which may wrongly interpret that the primary system is located out of the secondary user's interference range as the primary signal may be experiencing a deep fade or being heavily shadowed by obstacles as indicated by Molisch [1] and [6], [14]. Therefore, CRs have to be more sensitive to distinguish a faded or shadowed primary signal from a white space [16]-[18].

Ghasemi and Sousa [20], [25] have studied the cases where the SU is obliged to leave the channel immediately when the licensed user wants to use the channel. At this time if there is no other free channel for handovering the call in the vicinity of the SU, then the communication becomes aborted and the issue of reliability comes into question. Therefore to improve the reliableness of the cognitive radio network, the CR devices should be ready in advance before any communication starts [15], [19]. If the CR devices could establish a virtual wireless link with their neighboring CRs in order to report the trueness of the available free channels via the reporting channel to the central free channel database (CFCDB), then whenever a channel is to be accessed by the CR it can be provided.

The virtual point-to-multipoint wireless link between a single CR & many CR devices that are actually separated by an electrical distance (measured in wavelengths) is established before the actual communication starts. That is, through virtualization it is possible to build a virtual wireless network from abstract (logical) resources on top of a physical network constructed from physical resources [17]. The CFCDB continuously communicates with its CR devices to update its database and is in charge of the establishment of the virtual wireless link. Depending on the communication technology

the channel could be a frequency in FDMA (frequency division multiple access) system, a time slot in TDMA (time division multiple access) system & a code in CDMA (code division multiple access) system or a combination of these in a mixed system [20]. The CFCDB will be dedicated to monitor only a given geographical area together with a dedicated multi-Radio Access technology (multi-RAT) Base Station e.g. GSM (Global System for Mobile communications), UMTS (Universal Mobile Telecommunication Services) & LTE (Long Term Evolution) that is able to manage different systems at the same time and to be reconfigured accordingly where the hardware processing resources are shared among the supported RATs [24]. Reliability is improved because when one particular RAT within the cognitive radio network fails, it may still be possible to maintain a connection by falling back to another RAT as shown in [21],[22]. Spectrum efficiency is improved by making use of RATs which may have few users through the use of load balancing across RATs and coverage may be improved because different RATs may fill holes in coverage that any one of the single networks alone would not be able to fill [23].

II. SYSTEM DESIGN AND DESCRIPTION

The system under consideration is a collection of one or more wireless access networks. In order to quantify the throughput improvement gained by the establishment of VWLs in cognitive radio networks, a classical CRN is first described, and then the proposed network system model which uses the newly developed VWLS algorithm is presented.

A. The Classic Cognitive Radio Network Model

A cognitive radio network belonging to service provider j possesses wireless resources in the form of A_j channels. Connection-based traffic is considered, where service requirements of each flow or connection C_j is continuous and constant. Flows arrive at the network and request service. Each flow requires the capacity of one channel for the duration of its service in order to fulfil its requirements. If the CRN has available resources, it can accept the flow. If not, then the flow must be blocked – service is refused and the flow ends without being serviced. Once accepted, a flow must have continuous service for the duration of its service time [1]. The single network is depicted in Figure 1.

The classical CRN system consists of N classical networks. Each network has its own set of channels, with the total capacity of the system being $M = \sum_{i=1}^N A_j$. However, these networks are completely independent of each other, with

clients arriving to network j only being serviced on network j . As a result, when a network reaches its capacity, it must start blocking flows, as it has no available channels. Therefore, flows may be blocked even if the overall utilization of the total system (the complete set of N networks) is relatively low.

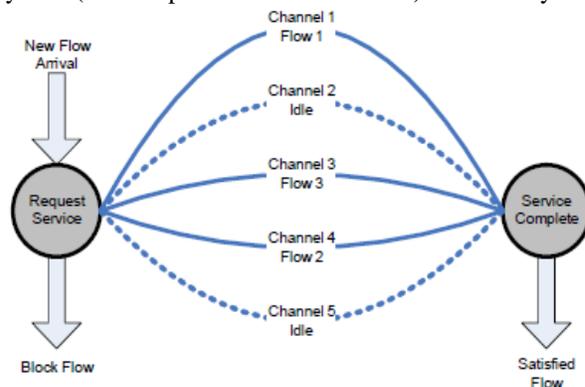


Figure 1: A Network with five Channels [1]

B. Design of the Proposed Cognitive Radio Network Model

The cognitive radio network system model for the proposed algorithm is depicted in Figure 2. The CFCDB is a fixed component in the cognitive radio system and has cognitive radio capabilities. It represents the infrastructure side of the CR system and provides supports (e.g. spectrum holes management, mobility management, security management) to CRs. It provides a gateway for CRs to access the backbone networks (e.g. Internet) via the multi-RAT base station. CFCDB can also form a mesh wireless backbone network by enabling wireless communications between them, and some of them act as gateway routers if they are connected with wired backbone networks.

B. Design of the Proposed Algorithm

In this section the steps of proposed virtual wireless link selection algorithm along with the network design will be presented. For the development of the algorithm we assume that there are only three bands available in the given local area. The steps to be executed in the VWLS algorithm are:

- i. Sense the available frequency bands in the local area (like GSM, UMTS or LTE) & keep them in the database
- ii. Calculate the probability of false alarm (P_{fa}) and the probability of correct detection (P_{cd}).
If $P_{fa} < 0.1$ and $P_{cd} > 0.9$ then go to step four, else if $P_{fa} \geq 0.1$ or $P_{cd} \leq 0.9$, then go to step two.

- iii. Measure the radio transmission parameters of the PU like power, modulation, coding, frequency
- iv. Check for the availability of free channels & Sort the free channels based on their signal strength (SNR)
- v. Report to the central free channel database via the reporting channel
- vi. Cooperate with neighboring CRs & with the CFCDB to establish a virtual wireless link on the free channel
- vii. Reconfigure its own radio parameters to match with that specific band for efficient transmission
- viii. Select the channel with the strongest signal or highest SNR and start transmission of voice or data. While transmitting, if the current channel is wanted by the PU, handover to another free channel. If there is no free channel for handovering the call is dropped
- ix. If either the call is ended or dropped, then go to step two.

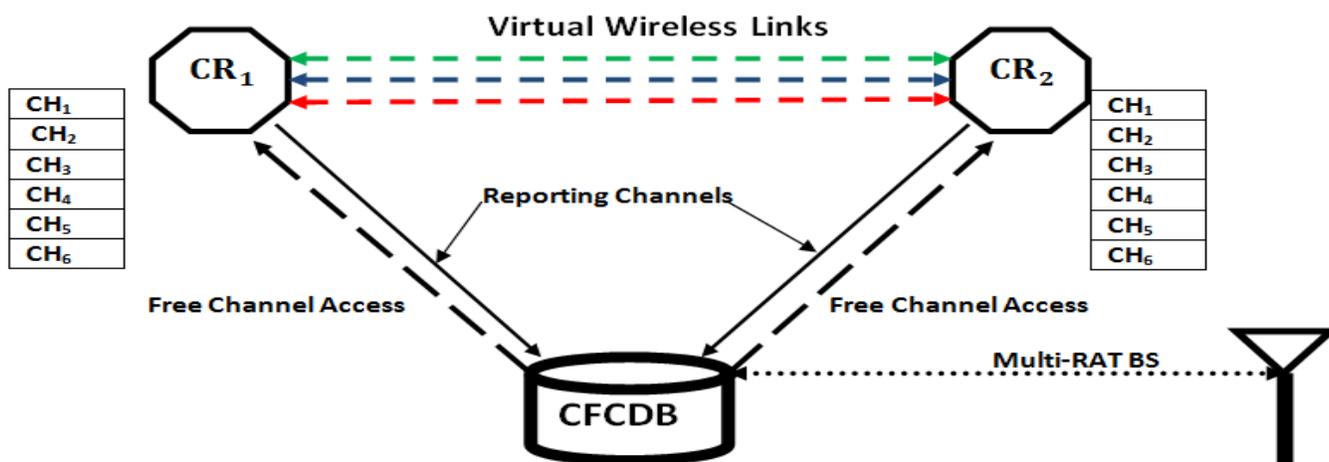


Figure 2: Cognitive Radio Network System Model for the proposed algorithm

Figure 2 above indicates the setup for the system model of the CRN. As can be seen in the figure, each CR device lists its free channels based on their signal strength and then report to the CFCDB through the reporting channels. During the virtual wireless link establishment, first the CFCDB collects channel information from all the CRs under its service area and broadcasts that information to the other CRs who do not know the channel information of a given CR. For example in our case above the CFCDB we have only two CRs, the CFCDB informs the channel information of CR₁ to CR₂ & the channel information of CR₂ to CR₁. Then CR₁ & CR₂ establish a virtual link between them based on the a priori knowledge of channel information.

III. CODING OF THE ALGORITHM

The next step is to code the VWLS algorithm using C++ programming language on the OMNET++/MiXiM platforms, where OMNET++ (Objective Modular Network Test bed in C++) is an object-oriented modular discrete network simulator and MiXiM (MiXed siMulator) is a

simulation framework for wireless and mobile networks which was developed on top of OMNET++ [26],[27].

A partial definition of module configuration is depicted in the Fig. 2 below.

```

simple CRBasePhyLayer like CRWirelessPhy
{
    parameters:
        double sensingtime @unit(s);
        bool coreDebug = default(false);
        bool recordStats = default(false);
        int headerLength = default(0) @unit(bit);
        bool usePropagationDelay;
        double thermalNoise @unit(dBm);
        bool useThermalNoise;
        xml analogueModels;
        xml decider;
        double sensitivity @unit(dBm);
        double maxTXPower @unit(mW);
        /* switch times [s]:
        double timeRXToTX = default(0) @unit(s);
        double timeRXToSleep = default(0) @unit(s);
        double timeTXToRX = default(0) @unit(s);
        double timeTXToSleep = default(0) @unit(s);
        double timeSleepToRX = default(0) @unit(s);
        double timeSleepToTX = default(0) @unit(s);
        int initialRadioState = default(0);
        double radioMinAtt = default(1.0);
        double radioMaxAtt = default(0.0);
        int nbRadioChannels = default(1);
        int initialRadioChannel = default(0);
    
```

Fig. 2 Partial example of a module definition (Basic Physical Layer Module)

During the development of the testbed, we included the parameters for the CRN that are to be implemented in the real network such as spectrum sensing time & the threshold signal level for correct reception.

A. Configuration of Primary and Secondary Users [1]

We configure both the cognitive users & primary users with the necessary transmission & reception parameters defined at the physical layer module. Fig. 3 below illustrates the partial configuration we did for the first primary user (PU1).

```

** PU1[*].nic.phy.sensingtime = 5s
** PU1[*].nic.phy.usePropagationDelay = true
** PU1[*].nic.phy.thermalNoise = -100dBm
** PU1[*].nic.phy.useThermalNoise = true
** PU1[*].nic.phy.analogueModels = xmldoc("config-template.xml")
** PU1[*].nic.phy.decider = xmldoc("deciderConfig.xml")
** PU1[*].nic.phy.sensitivity = -80dBm
** PU1[*].nic.phy.maxTXPower = 100.0mW
** PU1[*].nic.phy.initialRadioState = 0
** PU1[*].nic.phy.timeRXToTX = 0.00021s
** PU1[*].nic.phy.timeRXToSleep = 0.000031s
    
```

Fig. 3 Configuration of a primary user

B. The Simulation Diagram

After we did the entire configuration for all the radios, we run the simulation and the appearance of the network after coding looks like the one given in Fig. 4 below.

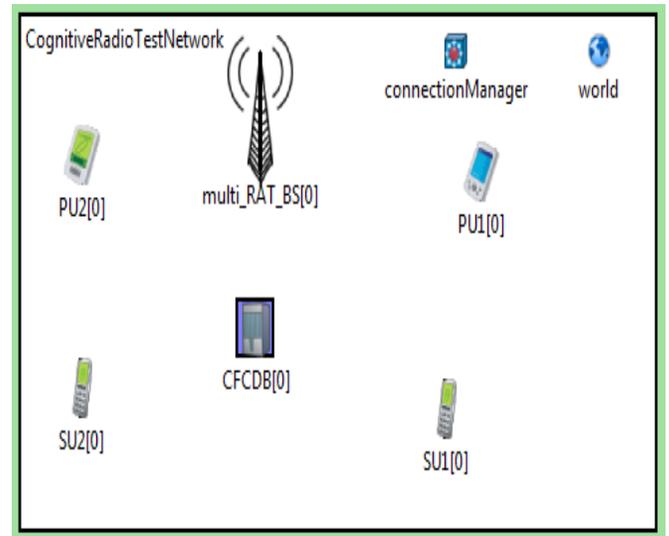


Fig. 4 Simple cognitive radio network design on OMNET++ Simulator

IV. SIMULATIONS RESULTS AND DISCUSSIONS

We investigate the performance of the VWL through the evaluation of the Secondary User Failure Probability (SU_{FP}) [2]. SU_{FP} is the probability that an arriving SU traffic (data or voice) will not receive the service it requires and it is calculated by using the blocking probability (P_B) & dropping probability (P_D). Blocking Probability is the probability that all radio channels are busy, in which case an arriving call is refused service & Dropping Probability is the probability that the SU traffic is dropped due to the reason that the channel is wanted by the licensed user or that there are not enough channels for handovering the call. SU_{FP} is used to compare the overall performance of SU and PU traffic and can be expressed as:

$$SU_{FP} = P_B + (1 - P_B) * P_D \tag{1}$$

Let N be the total number of free channels stored in the CFCDB and let M be the maximum number of virtual wireless links that could be established between the given CR nodes. We can approximate the SU_{FP} in terms of N and M as shown by the formula below:

$$SU_{FP} = \frac{1}{4N} \log_{10} 2M \tag{2}$$

From Eq. (1) and (2), we can conclude that as the number of free channels stored in the CFCDB increases, both the blocking and dropping probabilities decrease, thereby decreasing the SU_{FP} . The relationship between SU_{FP} , Number of free channels & the number of virtual wireless links (M) is depicted in the Figure 5.

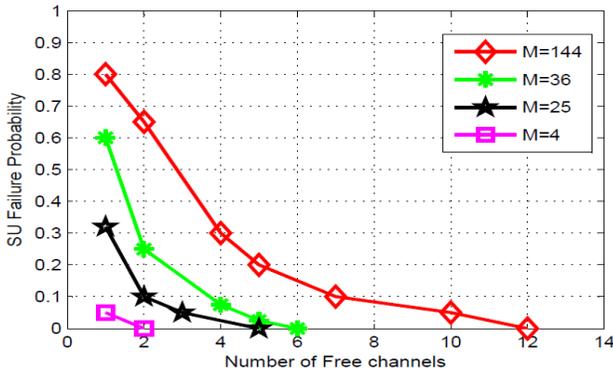


Figure 5: SU Failure Probability as a function of the number of free channels (N) and VWLs (M)

As can be seen in the figure, the resulting performance depends on both the number of primary users and the number of free channels stored in the CFCDB. As the number of free channels increases, SU failure probability decreases, as there is an increased probability that one of the networks has available resources. Second, increases in total number of virtual links result in an increase in the SU_{FP} . This is due to the fact that larger PU networks have a higher baseline utilization level than smaller networks, leaving a lower probability of having resources available for cognitive users.

A. Improvement in Number of Blocked Calls

The results of the simulation indicated that there is a decrease in the total number of blocked calls (back offs) in the secondary users due to the presence of the virtual wireless link as illustrated in Figure 6.

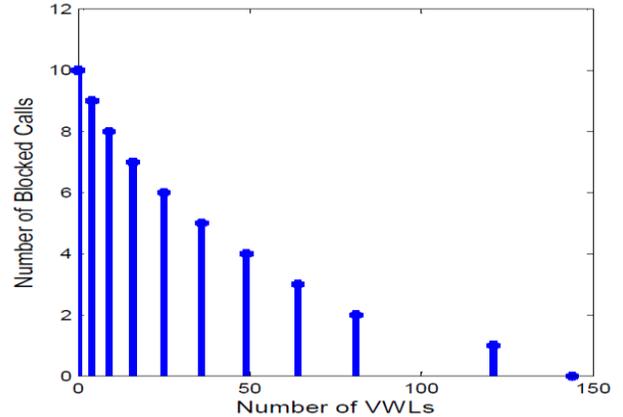


Figure 6: Number of blocked calls versus number of virtual wireless links

B. Improvement in Probability of Blocking and Probability of Failure

When a CR has a packet to transmit, it waits for a random backoff time before transmitting a request-to-send (RTS) packet to a desired receiver. The RTS contains the list of idle channels at the sender in the order of preference. The backoff value is selected within the interval $[0, CW]$, where CW denotes the CR's current contention window (CW) size. The CW is initially set to cw_0 (minimum CW) and is doubled with every retransmission up to cw_{max} . A receiver of an RTS, combines the preference list of the sender with its own, and replies with a clear-to-send (CTS) message that reserves the channel with the least number of reservations. CRs around the receiver overhearing the CTS update their channel preference list by degrading the priority of the selected channel [3]. The CR user monitors the spectrum band to detect when there is no transmission from the other CR users and transmits after backoff duration to prevent simultaneous transmissions. The backoff counter indicates the number of slots that the station has to wait before the transmission. As the number of VWLs increases, the backoff duration and the probability of blocking decrease approximately exponentially as illustrated in Figure 7 and Figure 8 respectively.

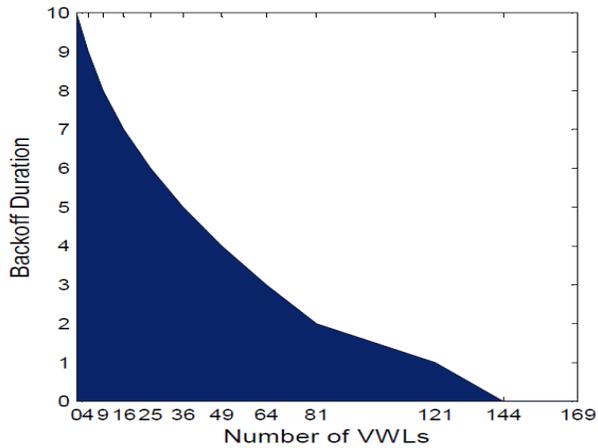


Figure 7: Backoff duration versus number of virtual wireless links

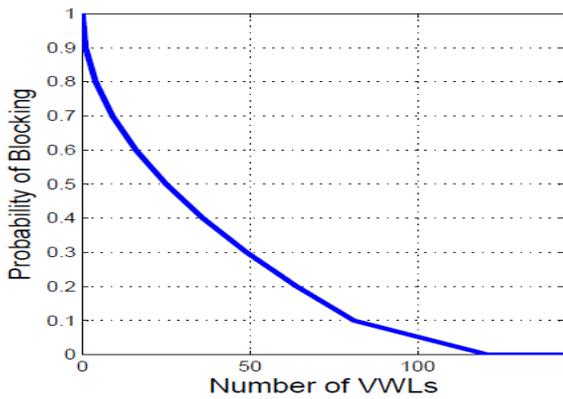


Figure 8: Probability of blocking versus number of virtual wireless links

As the number of free channels increases, the probability of failure in cognitive radio networks decreases as depicted in Figure 9.

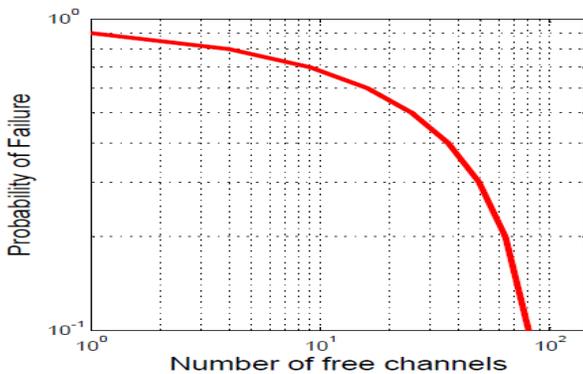


Figure 9: Probability of failure versus number of free channels

Cooperative users offering alternative paths for their partners can significantly improve link reliability and increase throughput without consuming extra resources. In the context of cognitive radio, secondary users opportunistically exploit the existence of spectrum holes to improve spectrum utilization. In Figure 10, the CRN system throughput increases when the number of available free channels stored in the CFCDB increases. Increased throughput means more efficient usage of power and spectrum. Overall, the throughput with the virtual wireless link structure is much larger than the one without a virtual wireless link structure.

As shown in Figure 11, system utility and throughput are improved in our approach in comparison with CRNs without a virtual wireless link. The one with the virtual wireless link structure increases faster than the one without the virtual wireless link over time. The simulation results verify our theoretical analysis and show that the efficiency of our approach is significantly improved compared with the one without a virtual wireless link.

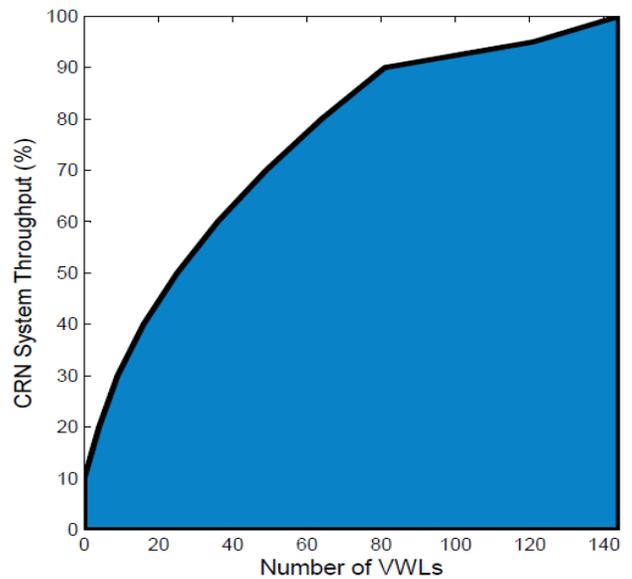


Figure 10: Cognitive radio network system throughput as a function of the number of virtual wireless links

V. CONCLUSIONS

We observed that the establishment of the VWL schemes improved the system throughput and when the number of

VWLs increases the system utility obtained improves as well. We showed that channel linking is generally beneficial for cooperative cognitive radio networks, though the extent of the benefits depend on the features of the CRN, including CRN size and the total number of channels available for linking. In addition, we showed that throughput benefits can be realized by adaptively changing the number of linked channels depending on network conditions.

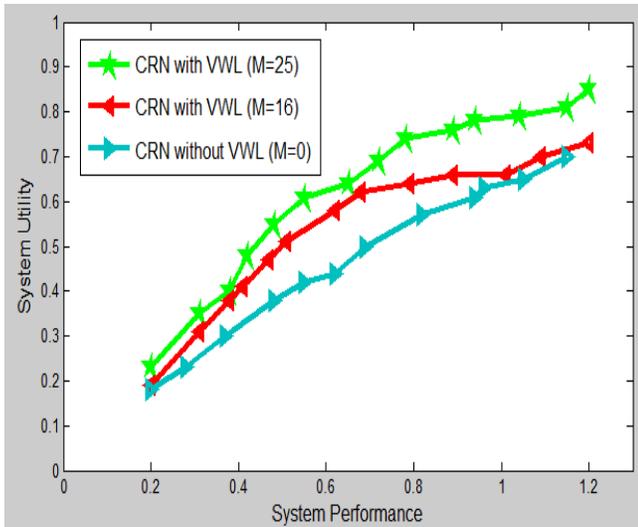


Figure 11: System utility as a function of system performance and number of virtual wireless links

REFERENCES

- [1] A. F. Molisch, *Wireless Communications*, 2nd ed. West Sussex, UK: John Wiley & Sons, 2011.
- [2] T. S. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed.: Prentice Hall, 2002.
- [3] A.J. Goldsmith, *Wireless Communications*. New York, USA: Cambridge University Press, 2005.
- [4] T. Yucek and H. Arslan, "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications," *IEEE COMMUNICATIONS SURVEYS & TUTORIALS*, vol. 11, no. 1, pp. 116-130, 2009.
- [5] R. Engelman, K. Abrokwhah, G. Dillon and G. Foster, "Report of the Spectrum Efficiency Working Group," Federal Communications Commission Spectrum Policy Task Force, 2002.
- [6] S. Senthuran, A. Anpalagan, and O. Das, "Throughput Analysis of Opportunistic Access Strategies in Hybrid Underlay-Overlay Cognitive Radio Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 6, pp. 2024-2035, June 2012.
- [7] J. Mitola III, *Software Radio Architecture*. New York, USA: Wiley Interscience, 2000.
- [8] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 23, no. 2, pp. 201-220, February 2005.
- [9] M. Subhedar and G. Birajdar, "SPECTRUM SENSING TECHNIQUES IN COGNITIVE RADIO NETWORKS: A SURVEY," *International Journal of Next-Generation Networks (IJNGN)*, vol. 3, no. 2, pp. 37-51, June 2011.
- [10] F. Khozeimeh and S. Haykin, "Brain-Inspired Dynamic Spectrum Management for Cognitive Radio Ad Hoc Networks," *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, vol. 11, no. 10, pp. 3509-3517, October 2012.
- [11] FCC, ET Docket No 03-222 Notice of Proposed Rulemaking and Order, 2003.
- [12] F.K. Jondral, "Software-defined radio-basic and evolution to cognitive radio," *EURASIP Journal on Wireless Communication and Networking*, vol. 1, no. 3, pp. 275-283, August 2005.
- [13] B.A. Fette, *Cognitive Radio Technology*, Second ed. USA: Elsevier Inc., 2006.
- [14] Y. Zeng and Y.C. Liang, "Spectrum-Sensing Algorithms for Cognitive Radio Based on Statistical Covariances," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 4, pp. 1804-1815, May 2009.
- [15] B. Rawat and G. Yan, "Spectrum Sensing Methods and Dynamic Spectrum Sharing in Cognitive Radio Networks: A Survey," *International Journal of Research and Reviews in Wireless Sensor Networks*, vol. I, no. 1, pp. 1-13, March 2011.
- [16] J. G. Proakis, *Digital Communications*, Fourth ed. Boston, MA: McGraw Hill, 2000.
- [17] D. Cabric, A. Tkachenko and R. Brodersen, "Spectrum sensing measurements of pilot, energy, and

collaborative detection," in *Proc. IEEE Military Commun. Conf.*, Washington D.C., 2006, pp. 1-7.

- [18] B. Choi, K. Kim and C. R. C. M. da Silva, Distributed Spectrum Sensing for Cognitive Radio Systems, 2007, Information Theory and Applications Workshop.
- [19] W. Zou, W. Wang, L. Zhang and Z. Zhou , "On the distributed cooperative spectrum sensing for cognitive radio," in *International Symposium on Communications and Information Technologies*, 2007, pp. 1496–1501.
- [20] A. Ghasemi and E. S. Sousa, "Asymptotic performance of collaborative spectrum sensing under correlated log-normal shadowing," in *proc IEEE Commun. Lett.*, vol. 11, no. 1, pp. 34-36, 2007.
- [21] M. Stella Iacobucci, *RECONFIGURABLE RADIO SYSTEMS, NETWORK ARCHITECTURES AND STANDARDS*, 1st ed., Giancristofaro Domenico and Lofrumento Giovanni, Eds. West Sussex, United Kingdom: John Wiley & Sons, Ltd, 2013.
- [22] ETSI TR 102 681, "Reconfigurable Radio Systems (RRS); Radio Base Station (RBS) Software Defined Radio (SDR) Status, Implementations, and Costs Aspects, Including Future Possibilities," ETSI, Technical v1.1.1, 2009.
- [23] Zhao Nan, Pu Fangling, and Xu Xin, "Optimisation of multi-channel cooperative sensing in cognitive radio networks," *IET Communications*, vol. 7, no. 12, pp. 1177-1190, May 2013.
- [24] D. Cabric, S. Mishra and R. Brodersen, "Implementation Issues in Spectrum Sensing for Cognitive Radios," in *Asilomar Conf. on Signals, Systems and Computers*, Pacific Grove, CA, 2004, pp. 772-776.
- [25] A. Ghasemi and E.S. Sousa, "Collaborative spectrum sensing for opportunistic access in fading environments," in *in proc First IEEE International Symposium on DySPAN*, 2005, pp. 131-136.
- [26] OMNeT++ User Manual version 4.3.1. [Online]. <http://inet.omnetpp.org/doc/inet-manual-DRAFT.pdf>
- [27] MiXiM official website. [Online]. <http://mixim.sourceforge.net/>