International Journal of Digital Information and Wireless Communications (IJDIWC) 4(2): 191-201
The Society of Digital Information and Wireless Communications, 2014 (ISSN: 2225-658X)

Interference Analysis and Spectrum Sensing of Multiple Cognitive Radio Systems

Sowndarya Sundar and M. Meenakshi
Department of Electronics and Communication Engineering
College of Engineering, Guindy Campus, Anna University
Sardar Patel Road, Chennai, INDIA
E-mail: sowndaryasundar@gmail.com

ABSTRACT

Conventional fixed spectrum allocation results in a large part of frequency band remaining underutilized. Channels that are dedicated to licensed (primary) users are out of reach of unlicensed users, while the licensed users do not occupy the channel completely, at all times. Cognitive Radio is an attractive concept and solution, capable of addressing this issue. This paper investigates a statistical simulation model for spectrum sensing of cognitive radio and the associated interference probability calculation methodologies. The capability to simulate multiple cognitive radio systems with issues of complex range of spectrum engineering and radio compatibility are explored. Simulations were carried out and output parameters such as sensing received signal strength, cell capacity and achieved bitrate were obtained and analyzed. The results were obtained for different conditions with particular emphasis on CDMA systems and OFDMA systems. The article also highlights the results obtained for studying detection threshold and the associated interference probability.

KEYWORDS

Cognitive radio; spectrum management; software radios; self-organizing networks; interference calculation

1 INTRODUCTION

With the exponential increase in the use of high powered wireless devices, the spectrum availability or rather, the lack of it is a major challenge. Conventional fixed spectrum allocation results in a large part of frequency band remaining underutilized. Channels that are dedicated to licensed (primary) users are out of reach of unlicensed users, while the licensed users do not occupy the channel completely, at all times. Cognitive radio is a concept that is capable of addressing this issue and is a form of dynamic spectrum management that attempts to utilize the channel in its full capacity.

The chief functions of cognitive radio are spectrum sensing and management. Through spectrum sensing, the cognitive radio becomes aware of its environment and sensitive to its changes. Spectrum sensing essentially involves checking within a candidate channel if any protected service is present and transmitting. When a channel is found to be vacant, sensing is typically applied to adjacent channels to identify if any constraints on transmission power are present. Spectrum sensing techniques can be classified as transmitter detection, cooperative detection, and interference-based detection [1].

A cognitive radio automatically detects the available channels in wireless spectrum, then accordingly changes its transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at a given geographic location. Radio-system parameters such as frequency, waveform and protocol are intelligently configured and monitored to determine the channel conditions and frequency environment, so that settings are adjusted to deliver the required quality of service subject to an appropriate combination of regulatory constraints, operational limitations, along with requirements of user.

To detect a primary user as well as to avoid any false alarm are of paramount importance for such a system. In reality, it is very difficult for a cognitive radio to have the information of direct measurement of a channel between a primary transmitter and receiver. One way to conduct a measurement within the candidate channel to find the presence or absence of any protected service is having the knowledge of a parameter, called detection threshold. For energy-detector based spectrum sensing, the threshold is set to distinguish signal from noise.

In the sensing based spectrum sharing model [2], in which only the radio-frequency spectrum is considered, a simple energy detector cannot guarantee the accurate detection of signal presence, necessitating complex spectrum sensing devices and periodical exchange of information about spectrum sensing. The changes in traffic or user movement demand updates to be done in the radio environment. The spectrum holes that are detected through spectrum sensing is to be followed up with analysis and decision making to determine parameters such as mode of transmission, data rate and bandwidth so that the spectrum band is chosen in accordance with requirements of user.

In addition to these technical challenges, the practical implementation of dynamic spectrum management must also conform to the rules and regulations set out for radio spectrum access in international law as well the legislation specified by respective countries.

2 RELATED WORK

2.1 Artificial Intelligence for Cognitive Radios

Application of Artificial Intelligent (AI) techniques to cognitive radio networks is a promising field of research since such networks should have the capacity to learn and adapt within any layer of the radio communication system. The application of various classes of AI techniques to cognitive radio networks can be found in the literature. Ref. [3] presented the adaptive component, which uses Genetic Algorithms (GAs) to evolve a radio defined by a chromosome whose genes represent the adjustable parameters in a given radio. The GA could find a set of parameters that optimize the radio for the user's current needs [3]. Ref. [4] described the physical components of the spectrum sensing network as well as the experimental system's information storage and learning mechanisms. It was pointed out that the spectrum sensing network of the project might be extended to a universal research platform for general cognitive radio devices, networks and applications. The hidden Markov model is applied for spectrum sensing [5]. An Artificial Neural Network (ANN) based and a Case Based System (CBS) based cognitive engines were presented as case studies in [6]. The paper also noted that a cognitive engine must carefully be designed, observing the tradeoff between performance and complexity determined by the application requirement.

2.2 Simulators

Simulation greatly helps in seeing how the systems and networks behave before actual implementation. Simulation tools have become an integral part of design and analysis in the domain of wireless systems. Studies on simulation of cognitive radio engine and networks have been reported in the literature. An infrastructure-based cognitive radio network consisting of one base-station and multiple users was simulated in [7]. Simulation results showed that the proposed spectrum decision framework provided efficient bandwidth utilization while guaranteeing the service quality [7]. The simulator in the project [8] was built in object oriented language and the purpose was to simulate what could happen if the cognitive users were allowed to transmit freely in reality. The thesis also evaluated the simulator with some realistic values, simulating radio traffic for certain frequencies in environments of the size of cities or big country sides.

Ref. [9] proposed and demonstrated the advantages of a new random motion generator for use in ns2 simulator for simulation of wireless mobile networks. An existing ns-2 network simulator was extended to support cognitive radio network simulation in [10]. The article suggested that simulators such as OPNET, QUALNET were created for the ordinary wireless network and hence researchers could not easily implement their cognitive radio algorithms over those simulators. A procedure that can be employed to generate artificial time-frequency spectrum data in simulation tools was presented in [11]. The authors assumed a generic simulation scenario and illustrated a possible simulation method to generate artificial spectrum data based on the presented models.

A new received signal strength (RSS) estimation method based on neural network was presented in [12] for the antenna placement problem in vehicle-to-vehicle communications. The article also suggested that the computation time of the proposed approach was much less than the ones of the RSS simulator. Ref. [13] demonstrated how the existing software radio projects could be leveraged to use the baseband modem in a wide range of radio frequency bands. The paper also described their approach and implementation of power management and instrumentation, a key building block in their modularized low-power software radio platform. Some current developments of wireless communication technology such as short range communication, cloud computing, bring your own device policy (BYOD), devices tethering and convergences of WiFi and cellular network technology were presented in [14]. Ref. [15] presented a strategy by means of infrastructure sharing between operators considering sharing the backhaul network infrastructure to improve resiliency among the operators. Despite the resiliency mechanisms, there are occasions when the network resources are not available for the end users which necessitates the need for sharing another operator's backhaul, thus decreasing the overall unavailability time [15].

3 SIMULATION

For radio compatibility, the interference in the victim receiver input is mostly the unwanted emissions from the transmitters as well as blocking and intermediation, considering only the adjacent bands. The analytical and classical approaches for the estimation of these interference mechanisms treat the operation of radio communications systems static, without taking into account the user movement on mobile systems and hence they are rigid and difficult to implement. Even with reasonable assumptions and simplifications, the accuracy of such interference assessment is impacted by the order and settings of priorities taken in making those assumptions and simplifications.

Simulations have been done in this article, by Spectrum Engineering Advanced Monte-Carlo Analysis Tool; a statistical simulation model developed originally using the C++ programming language [16]. The software tool provides adequate universality including the capability to directly simulate proliferating Code Division Multiple Access (CDMA) systems which have complex power control mechanisms in them.

The basic principle of the algorithm is centered on the detection threshold parameter that is used by a cognitive device to detect the presence of a protected service's transmission, if any. If it detects no emission above this threshold in a channel, the white space device (WSD) is allowed to transmit; otherwise the WSD keeps silent or looks into other channels. The algorithm assumes that frequency of the interfering WSD is dependent on the frequency range defined for the victim and there are many ways in which the operating frequency of the victim device can be defined; constant, discrete as specified by the user or it can be distributed between frequency limits dictated by the number of possible channels that the WSD will operate in. Similarly, the detection threshold can be defined either as a constant or a user-defined function.

Once the frequencies that are to be tested are identified, if the signal transmitted by the wanted transmitter to the victim receiver is found to be greater than sensitivity, the signal transmitted by wanted transmitter and sensed by interfering transmitter is calculated for each WSD for all its possible channels as per (1), considering the unwanted mask of the Digital Terrestrial Television (DTT). Here, *sRSS*- the sensing Received Signal strength; P_{Wt} - the transmit power from the Wanted Transmitter (*Wt*); f_m - the frequency of the WSD; $G_{Wt\rightarrow It}$ – the antenna gain of the *Wt*, in the *Wt* to *It* direction; $G_{It\rightarrow Wt}$ - the antenna gain of the Interfering transmitter (*It*) in the *It* to *Wt* direction; *L*- the path loss in dB between the *It* and the *Wt*.

$$sRSS\,(f_m) = P_{Wt}\,(f_m) + G_{Wt\rightarrow It} + G_{It\rightarrow Wt} + L \qquad (1)$$

The sRSS output vector so calculated for each WSD is shown in Fig.1. The figure shows the results when five WSDs are considered. This is followed by the detection of channels in which a WSD is allowed to transmit by comparing to threshold as stated earlier. Constraints on transmission power are then determined and interference is calculated.

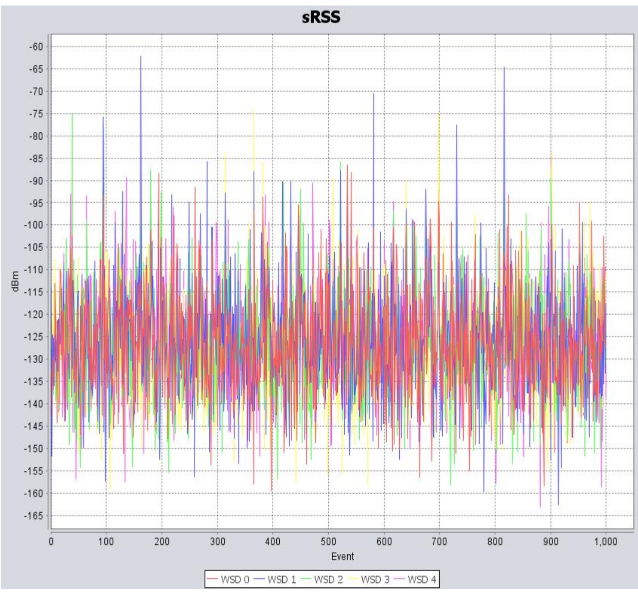

Fig. 1. Sensing received signal strength output for white space devices (vs) dBm

In the simulation, multiple interferers are set as cognitive radio devices when the interferer is not either CDMA or Orthogonal Frequency-Division Multiple Access (OFDMA). When an interferer is set as cognitive radio, the power and emission characteristics of the interfering WSD are input and if a victim system is detected in the vicinity, an appropriate operating frequency is selected and its emission mask is lowered as per the Effective Isotropic Radiated Power maximum (EIRP max) limit defined in spectrum sensing characteristics. Accordingly, detection threshold, probability of spectrum sensing failure and bandwidth of the sensing device are defined. The actual frequencies at which WSDs are allowed to transmit, victim frequency, sRSS etc. can be displayed in the form of a vector, cumulative distribution function (CDF) or probability density function. The densities of frequencies of various WSDs are as shown in Fig.2.

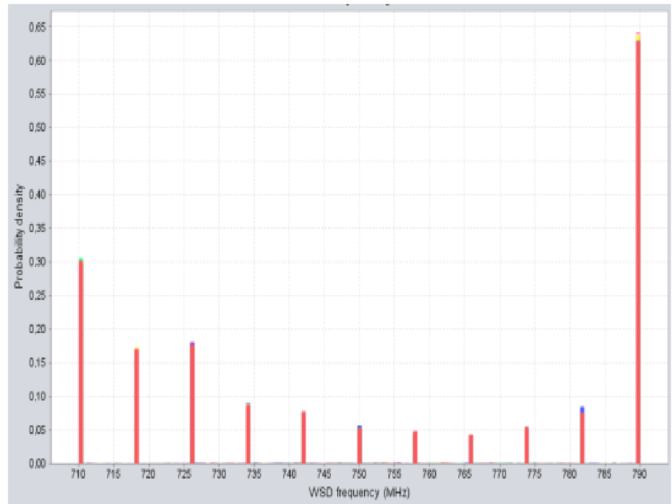

Fig. 2. Frequency density of white space devices; WSD Frequency (MHz) (vs) Probability density

Fig. 3 depicts CDF of the frequency at which the victim device transmits per event.

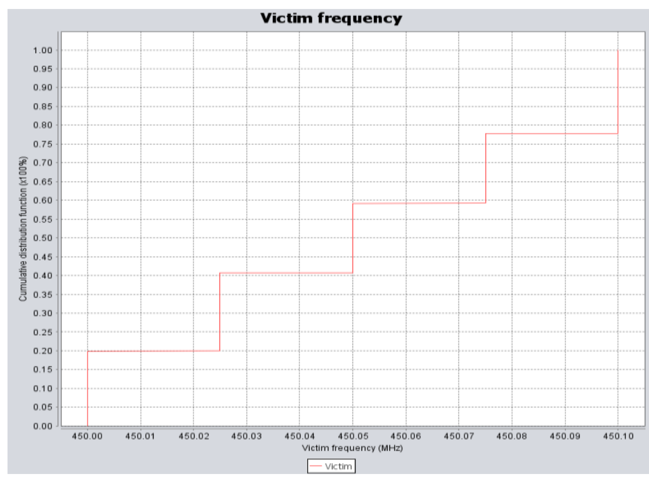

Fig. 3. Frequency density of white space devices; victim frequency (MHz) (vs) CDF

4 RESULTS

Once the output vectors are read, the user can perform interference calculation in the simulator engine. The victim link and interfering links were set up and the results were obtained for different conditions.

4.1 Co-channel Interference between Fixed Links

The interferer was set as cognitive radio which had seamlessly acquired the signal strength since the receiver and transmitters were fixed lines and optimally utilized the spectrum in locations not used. The parameter EIRP max was input with three parameters offset (MHz), Mask (dBm) and reference bandwidth of DTT (kHz). The probability Density Function (PDF) function is shown in Fig. 4.

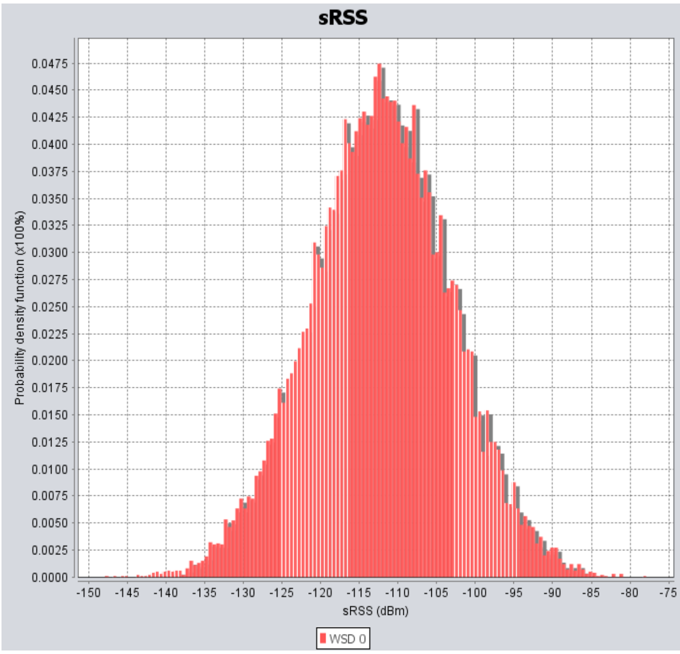

Fig. 4. Probability Density Function for fixed mobile links

4.2 Interference between Mobile Links

When the cognitive radio and the victim link are mobile, the determination and capture of signal becomes more time consuming when compared to fixed lines. The simulator was able to do this function satisfactorily as demonstrated in Fig. 5. As can be seen from the figure, not all simulated WSDs were active subject to an EIRP limit specified in the spectrum sensing characteristics. Similarly, the average EIRP per event can also be displayed.

4.3 Interference to CDMA System

CDMA systems offer high capacities compared to other competing digital (TDMA) and analog (FM) technologies. The CDMA capacity is interference-limited and any reduction in multiple access interference converts directly and linearly to an increase in capacity. A scenario was simulated wherein the victim link was considered to be a downlink component of CDMA-based mobile communications system at 1932.5 MHz band, which was potentially interfered by a co-channel operation of multiple short range devices deployed in the same geographic area. The environment chosen was rural and the antennas were outdoor and on the rooftop. Provisions were made to set the wall loss; indoor to indoor and indoor to outdoor. The simulation results include external interference due to unwanted signals and selectivity.

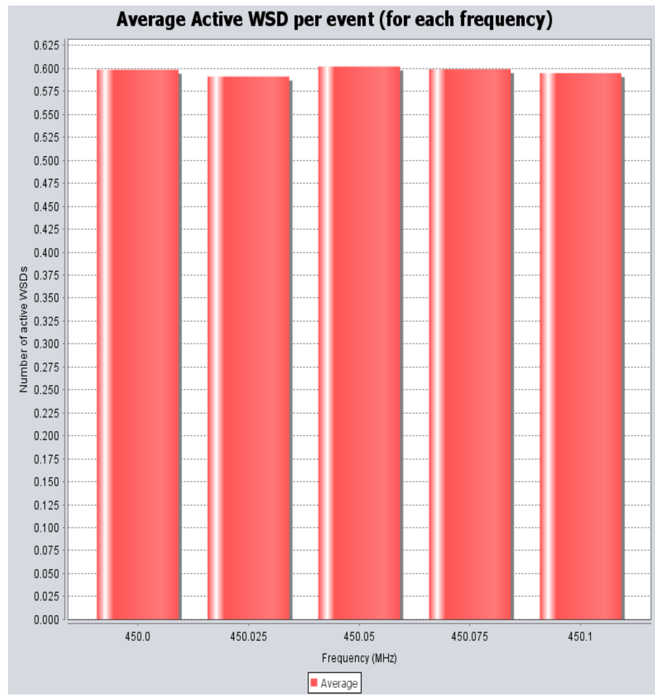

Fig. 5. Average number of active white space devices for each frequency

The simulator was able to yield CDMA specific results in two forms; capacity (Fig. 6) and outage (Fig. 7). While the capacity graph shows the number of mobile users optimally served in the reference cell before and after the introduction of interference, the ratio of non-connected mobile users to the total number of mobile users assigned to that cell before and after the introduction of external interference is shown in outage plot. Here, the reference cell is taken to be the centre cell of CDMA cluster, by default, but any other cell can also serve as reference. The excess outage due to impact of external interference is reflected in the parameter, average capacity loss (in %) which also indicates whether the interference to CDMA system is tolerable or not. In interference-limited systems, outage probability and capacity are fundamental parameters used in system analysis.

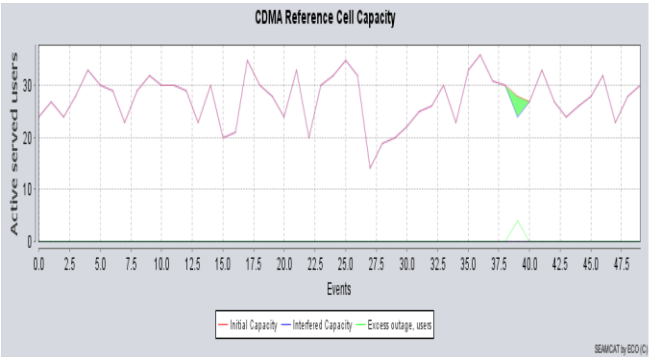

Fig. 6. Results of CDMA interference; cell capacity

One important highlight of CDMA simulation is that the display is highly interactive where all the pertinent details about an element such as a mobile station or a base station as well as the general statistics for the system as a whole namely, non-interfered capacity, number of generated mobile users, etc. can be obtained. The data pertaining to external interferers can also be extracted.

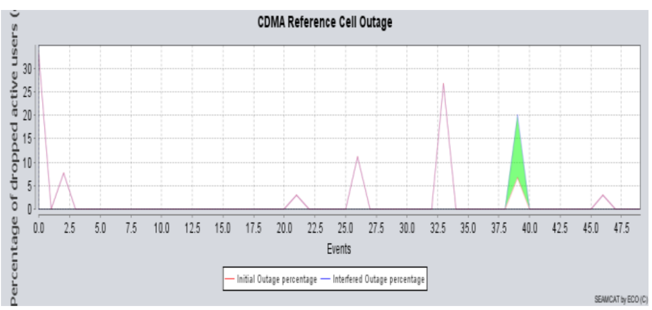

Fig. 7. Results of CDMA interference; outage (%)

4.4 Interference to OFDMA system

In OFDMA systems, due to the multiuser diversity gains and better handling of frequency selective fading, overall performance is improved. OFDMA can prevent multipath interference with better robustness and achieve higher MIMO spectral efficiency compared to CDMA. The results of the OFDMA simulation are given in terms of capacity/throughput loss of the OFDMA victim. Under this condition, the victim link was considered to be an uplink component of OFDMA-based mobile communications system. OFDMA simulation involves an iterative process of assigning a variable number of sub-carriers and calculating the overall traffic per base station, after the overall two-tiers cellular structure is built and populated with mobile stations. The UEs (user equipment) are deployed randomly in the whole network region according to a uniform geographical distribution and wrap-around technique is employed to remove the network deployment edge effects. The simulation can be performed for different cell layouts such as 2-tier 3GPP (specifies standards encompassing Radio, Core Network and Service architecture) and 2-tier 3GPP2 (specifies standards based on CDMA 2000) with specific cell radii. The simulation results for each case present the evolution of the achieved bitrate (in kilobits per second) in the reference cell per event and the evolution of the achieved bitrate for the whole system per event. Fig. 8, Fig.9 and Fig.10 show the simulation results for different cell layouts namely 2-tier 3GPP with a cell radius of 5 km, 2-tier 3GPP with a cell radius of 0.5 km, and 2-tier 3GPP2 with a cell radius of 0.5 km. respectively.

Fig. 8. Achieved bitrate (kbps) for 2-tier 3GPP system with a cell radius of 5 km; Reference cell (top plot), whole system (bottom plot)

In addition, simulations can be done and the user can extract various vectors for post analysis. These vectors are for the analysis of the achieved bitrate (with or without external interference) and the cell capacity (i.e. the number of active users per cell) with or without interference. The vectors such as average interfered bitrate, average non-interfered bitrate, coupling loss percentile, interfered capacity, non-interfered capacity and signal to interference plus noise ratio (SINR) can be generated for the reference cell in particular or for the whole OFDMA system. The achieved bit rate is calculated as shown in (2).

$$BiteRate = \frac{N_{subcarriersperUE}}{N_{totalsubcarriers}} * (x)_{SINR} * BW \quad (2)$$

Here, x is the spectral efficiency (in bps per Hz) with respect to calculated SINR and a conversion factor for bps to kbps also to be included.

Fig. 9. Achieved bitrate (kbps) for 2-tier 3GPP system with a cell radius of 0.5 km; Reference cell (top plot), whole system (bottom plot)

Thus, a summary of the average capacity and average bit rate loss expressed in percentages for both the reference cell and the entire OFDMA network (i.e. the whole system) can be obtained. The percentage calculation is performed for each event and the mean of the percentage over all the events is deduced. The results for the three cases are shown in Table 1.

Table 1. Average bitrate loss (in %) for different cell layouts and cell radii

Cell layout	Cell Radius (km)	For Reference Cell (%)	For OFDMA system (%)
2 tiers, single sector	5	100	21.628
2 tiers, single sector	0.5	85.247	27.096
2 tiers, 3GPP	5	100	11.731
2 tiers, 3GPP	0.5	86.422	9.159
2 tiers, 3GPP2	0.5	74.154	8.904

By observing the table, we deduce the relationship of the average bitrate loss with cell layout and cell radius. We can see that the lowest bitrate loss corresponds to the 3GPP2 system with the least cell radius. The 3GPP and single sector systems yield higher bitrate losses. On reducing the cell radius further, we can further reduce the bitrate loss.

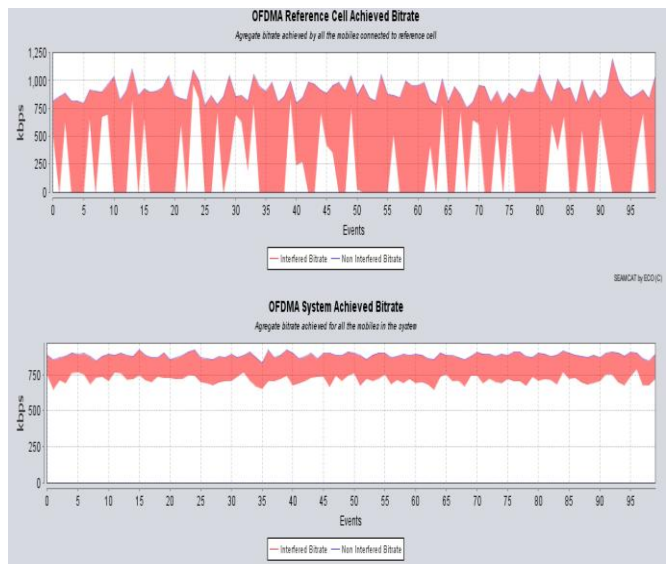

Fig.10. Achieved bitrate (kbps) for 2-tier 3GPP system with a cell radius of 5 km; Reference cell (top plot), whole system (bottom plot)

Simulations were also performed for a system with OFDMA uplink victim and OFDMA uplink interferer. A 2 tier 3GPP2 cell layout was chosen and a free space propagation model was considered. Fig. 11 shows the evolution of the achieved bitrate in kbps for the reference cell and the entire system. This particular simulation resulted in an average bitrate loss of 0.382% for the reference cell and 0.287% for the overall system.

Fig. 11. Achieved bitrate (kbps) for OFDMA UL victim-OFDMA UL interferer system; Reference cell (top plot), whole system (bottom plot)

We can also analyze the signal-to-interference-plus-noise ratio (SINR) of the victim reference cell and the victim system from the simulation results. Fig. 12 and Fig. 13 depict the probability density for different values of SINR for the victim reference cell and the victim system respectively.

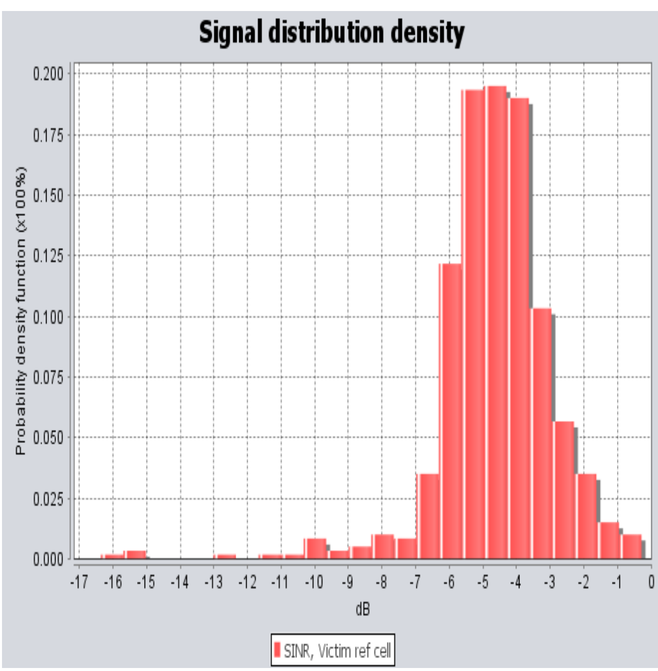

Fig. 12. Probability density function (%) (vs) SINR(db) for the victim reference cell.

The figures show that the SINR levels due to interference from the OFDMA UL interfering links for the particular scenario are mainly around -5db, with a highest value of around 0db, for both the reference cell and the overall system.

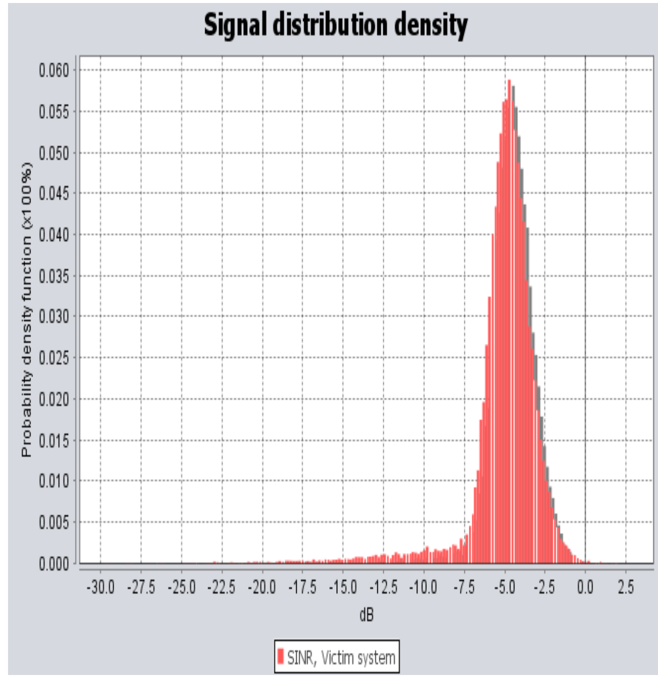

Fig. 13. Probability density function (%) (vs) SINR(db) for the victim system.

4.5 Detection threshold analysis and interference calculations

A scenario was set up involving a single victim link and several white space devices. The interferers were set as cognitive radios and the parameters of the victim and the interfering links were adjusted appropriately. The simulation was performed for different values of detection threshold and the interference calculations were obtained. The simulation results shown are for three different values of detection thresholds, namely, 50, 0 and -100. Fig. 14 and Fig 15 show the results for a detection threshold of 50.

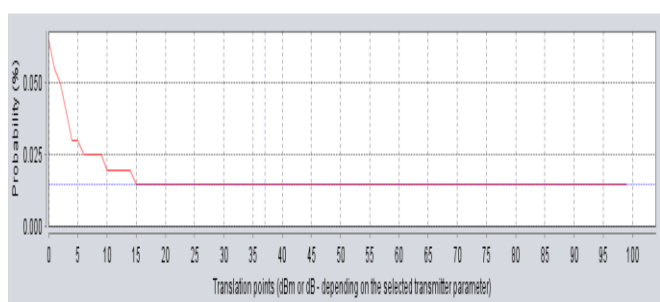

Fig. 14. Probability (%) (vs) blocking response level/victim link for detection threshold of 50

The type of interference signal chosen for calculations was both unwanted and blocking. The calculations were performed in both the compatibility mode and translational mode to aid in analysis.

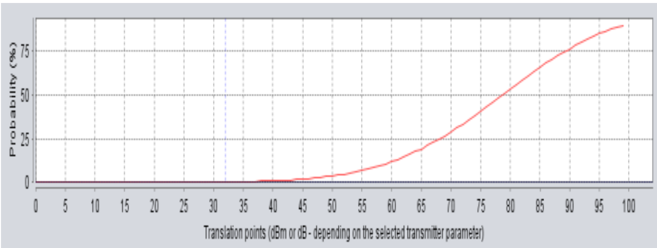

Fig. 15. Probability (%) (vs) power supplied/ CRS transmitter for detection threshold of 50

Fig. 16 and Fig. 17 display the results for a detection threshold of 0 and Fig. 18 and Fig. 19 for a detection threshold of -100.

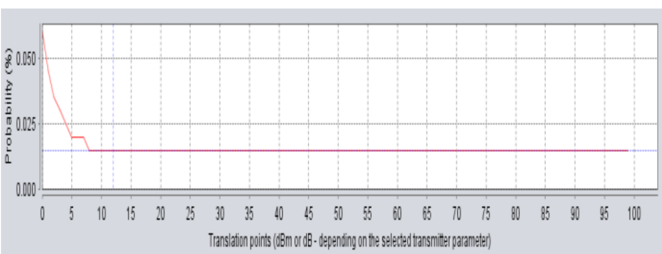

Fig. 16. Probability (%) (vs) blocking response level/victim link for detection threshold of 0

The figures 14, 16 and 18 indicate the probability of interference as a function of blocking response level of the victim receiver whereas the figures 15, 17 and 19 indicate the probability of interference as a function of output power of the interfering transmitter.

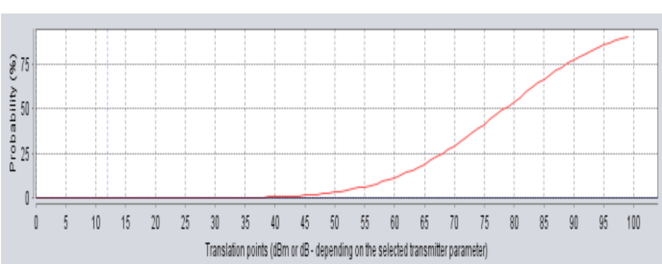

Fig. 14. Probability (%) (vs) power supplied/ CRS transmitter for detection threshold of 0

The summary of the compatibility results which comprises of a single interference probability value for each detection threshold, are shown in Table 2.

Table 2. Interference probability in compatibility mode for different values of detection threshold

Detection threshold	**Interference probability (%)**
50	0.07
0	0.06
-100	0.0

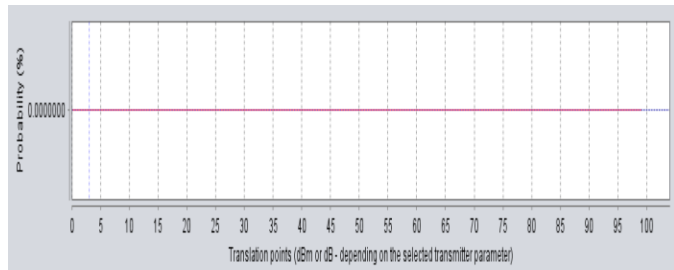

Fig. 18. Probability (%) (vs) blocking response level/victim link for detection threshold of -100

The simulation results showed that the probability of interference reduces with reduction in detection threshold and a detection threshold of -100 or less yield zero probability of interference for the scenario. Instead of choosing a constant detection threshold value, the threshold can be made adaptive or as a function of other parameters in order to yield better results.

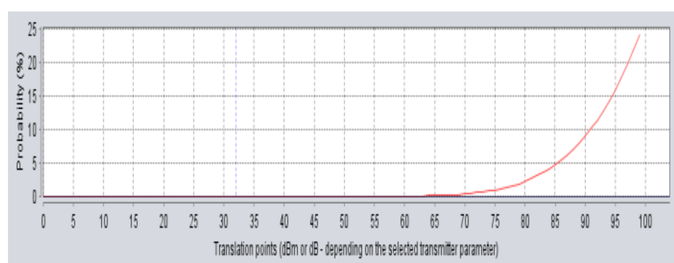

Fig. 19. Probability (%) (vs) power supplied/CRS transmitter for detection threshold of -100

5 DISCUSSION and FUTURE WORK

The simulation model supported multiple radio systems and compatibility. The spectrum sensing phenomenon where the interfering devices try to detect the presence of protected services transmitting in each of the potentially available channels was incorporated in the model by inclusion of detection threshold and the selection of operating frequency of the white space device. The simulator model uses an effective algorithm to detect the presence or the absence of a protected service's transmission. If it detects no emission above this threshold in a channel, the white space device is allowed to transmit; otherwise the white space device keeps silent or looks into other channels.

The simulator model took spatial and temporal distributions of the received signals into account and the statistical probability of interference was examined for a wide variety of scenarios. The various output features such as sensing received signal strength, WSD frequency and its density, CDF of victim frequency, EIRP, average EIRP per frequency and average active WSDs per frequency gave useful information about interference assessment. In the case of an interferer being set as a cognitive radio, the spectrum sensing characteristics included EIRP max which is an important parameter to see if a radio solution is within the values allowed by local regulatory bodies.

The model was able to simulate more precise mutual positioning of the systems under consideration, hence demonstrated the efficiency of use of radio spectrum. It was seen that the issues of complex range of spectrum engineering and the corresponding radio compatibility were able to be dealt with. Though the model exhibited highly interactive features in simulating CDMA and OFDMA systems including that of individual element details and whole system characteristics such as average capacity loss and average bitrate loss, it lacked the ability to simulate CDMA/OFDMA as victim and cognitive radio interferer. This unconventional setting can be included in the future algorithm. The time complexity of calculations in the CDMA/ OFDMA module can also be improved with enhancement in the detection algorithm.

In addition, interference analysis and compatibility for different cases were explored and analyzed with the help of the Interference Calculation Engine. Adaptive detection threshold values can be implemented and studied for better interference management. A more accurate interference assessment also would pave the way for the design of efficient interference mitigation mechanisms.

6 CONCLUSION

Cognitive radio is capable of addressing the challenges associated with the fixed spectrum assignment policies in today's wireless domain. It has to be able to change the waveform and operational parameters in accordance with environmental and user changes and to examine sensory input, to learn and adjust inner operations. The chief functions of cognitive radio are spectrum sensing and management. While the cognitive radio becomes aware of its environment through spectrum sensing, the learning and adaptability is attained by having artificial intelligence capabilities.

Simulation tools have become an integral part of design and analysis in the domain of wireless systems. This article investigated a statistical simulation model, its algorithm and output features in detail and found that it provided adequate universality including the capability to simulate CDMA systems that have complex power control mechanisms. In this paper, OFDMA specific results were analyzed for different cell layouts and cell radii and the average bitrate losses, for the reference cell as well as the overall system, for some of the cases were compared. The model supported sufficient interference probability calculation though its engine. This allowed the simulation of different scenarios by varying the detection threshold and monitoring the interference probability using both the compatibility and translational modes.

The practical implementation of dynamic spectrum management must also conform to the rules and regulations set out for radio spectrum access in international law as well the legislation specified by respective countries. With more research and refinement happening in spectrum sensing, decision and management, the resulting simulation models of cognitive networks will shape the communication technologies and protocols of future.

7 REFERENCES

1. Akyildiz, I. F., Lee, W. Y., Vuran, M. C., Mohanty, S.: NeXt Generation/Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey. Computer Networks 50, 2127-2159 (2006).

2. Kang, X., Liang, Y., Garg, H. K., Zhang, L.: Sensing-Based Spectrum Sharing in Cognitive Radio Networks. IEEE Transactions on Vehicular Technology 58, 4649-4654 (2009).

3. Rondeau, T. W., Le, B., Rieser, C. J., Bostian, C. W.: Cognitive Radios with Genetic Algorithms: Intelligent Control of Software Defined Radios. In: Proc. SDR 04 Technical Conference and Product Exposition, Phoenix, USA (2004).

4. Brendel, J., Riess, S., Stoeckle, A., Rummel, R., Fischer, G.: A Spectrum Sensing Network for Cognitive PMSE Systems. Jondral, F. K., Mühlhaus, M. S. (eds.), Frequenz, vol. 66, no. 9-10, pp. 269-278 (2012).

5. Kim, K., Akbar, I. A., Bae, K. K., Urn, J., Spooner, C. M., Reed, J. H.: Cyclostationary approaches to signal detection and classification in cognitive radio. In: Proc. the 2nd IEEE International Symposium on New frontiers in Dynamic Spectrum Access Networks (DySPAN), pp.212–215, Dublin, Ireland (2007).

6. He, A., Bae, K., Newman, T., Gaeddert, J., Kim, K., Menon, R., Morales, L., Neel, J., Zhao, Y., Reed, J., Tranter, W.: A Survey of Artificial Intelligence for Cognitive Radios. IEEE Transactions on Vehicular Technology, Special Issue on Cognitive Radio 59, 1578-1592 (2010).

7. Lee, W., Akyildiz, I. F.: A Spectrum Decision Framework for Cognitive Radio Networks. IEEE Transactions on Mobile Computing 10, 161-174 (2011).

8. Sundman, D.: A Simulator for Cognitive Radio. Master's degree project, KTH Electrical Engineering, Stockholm, Sweden (2008).

9. Alghamdi, R., DeDourek, J., Pochec, P.: Evaluation and Improvements to Motion Generation in ns2 for Wireless Mobile Network Simulation. International Journal of Digital Information and Wireless Communications 2, 84-92 (2012).

10. Chigan, C.: Development of NS-2 Based Cognitive Radio Cognitive Network Simulator. Co-PI: Project Partially Supported by US Army Communications-Electronics Research Development and Engineering Center (CERDEC).

11. López-Benítez, M., Casadevall, F.: Spectrum Usage Models for the Analysis, Design and Simulation of Cognitive Radio Networks. In: Venkataraman, H., Muntean, G. M. (eds.), Cognitive Radio and its Application for Next Generation Cellular and Wireless Networks, Lecture Notes in Electrical Engineering, DOI: 10.1007/978-94-007-1827-2_2, Springer Science+Business Media, Dordrecht (2012).

12. Talepour, Z., Kondori, H., Barakati, M., Mehrjoo, M., Shokouh, J. A.: Received Signal Strength Estimation in Vehicle-to-Vehicle Communications Using Neural Networks. International Journal of Digital Information and Wireless Communications 3, 42-47 (2013).

13. Szilvási, S., Babják, B., Lédeczi, A., Völgyesi, P.: Towards a Versatile Wireless Platform for Low-power Applications. International Journal of Digital Information and Wireless Communications 1, 401-414 (2011).

14. Noor, M. M., Hassan, W. H.: Wireless Networks: Developments, Threats and Countermeasures. International Journal of Digital Information and Wireless Communications 3, 119-134 (2013).

15. Philip, V. D., Yvon, G., Djamal, Z.: Infrastructure Sharing: A Cost Effective Alternative for Resiliency in 4G-LTE Mobile Networks. International Journal on New Computer Architectures and Their Applications 2, 113-126 (2012).

16. http://seamcat.iprojects.dk/wiki/Manual