Learning Based Spectrum Utilization in Underlay Cognitive Radio Network

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May Allah bless them all with eternal happiness!

DEDICATIONS

To My Father late, Mother, Family and Friends.

ABSTRACT

Spectrum access strategy plays a critical role in multichannel cognitive radio networks (CRNs). The Cognitive radio is a key solution for radio spectrum under-utilization problem. It aims to increase the QoS of the system. In underlay scheme the primary user (PU) and secondary users (SU) can access the spectrum and communicate concurrently. However, SU's established the threshold for not initiating interference to PU called interference temperature. In this way the unlicensed user accesses the licensed spectrum to efficiently utilizes the resources without interfering the PU. The SU has to sense continuously the spectrum hole, which can result in delay and energy consumption. In this proposal, we propose an efficient spectrum utilization scheme based on Q-learning to maximize throughput and minimize energy and delay.

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ABBREVIATIONS

DSA	Dynamic spectrum access
RF	Radio frequency
PU	Primary user
SU	Secondary user
PN	Primary network
SN	Secondary network
FCC	Federal communication commission
CRN	Cognitive radio network
CSI	Channel state information
IT	Interference threshold
UCB	Upper confidence bound
OS	Opportunistic scheduling
MS	Multicast scheduling
QoS	Quality of services
SNIR	Signal to noise interference ratio
RA	Resource allocation

Chapter 1

Introduction

1.1 Overview

The common natural source for transmission and receiving of data using the spectrum is the electromagnetic radio frequency (RF) which is used by government and other private organization for transmission and receiving of data under the licensed frequency band [1]. Two types of spectrum access exist. Static spectrum access and dynamic spectrum access. In static spectrum access the policies are strict and fixed channels are assigned to the PU to use under licensed spectrum and SU to use unlicensed frequency band, the SU to use licensed band is strictly prohibited. But with the rapid deployment of the wireless network, the spectrum access has become common challenge because the recent frequency allocation techniques cannot accommodate increasing demand of the high data rate. Therefore, the current spectrum utilization techniques have very low efficiency due to static spectrum polices.

The main components of the cognitive networks are Primary and Secondary network (PN), (SN). PU [1]-[2], is the licensed user that access its own available spectrum. And the secondary used is the un-licensed user which uses licensed band of PU for its transmission but under some pre-defined threshold. The primary network does not know the existence of secondary network know as transparency of a network.

For spectrum underutilization problem the cognitive radio network is an efficient and innovative technology and the dynamic spectrum access (DSA) is proposed which is a hot topic for both the industry and as well as academia for recent years. All these works are to develop a technique in which SU is allowed with PU to communicate concurrently and get equal opportunities in frequency, and time domain and cause minimum intrusion to primary user.

The cognitive radio networks models have three different types [3]. Interwave, underlay and overlay to solve the spectrum utilization problem. In Interwave cognitive network model, the PU band is not allowed by SU. However, federal communication commission (FCC) is working to maintains the availability of SU to access the spectrum band in the absence of PU. However, the main problem is that the CR needs to continuously sense the spectrum to identify the spectrum holes to utilized them at instant time and location. The spectrum sensing is the key feature of this model to detect the spectrum holes when the PU is not present and utilize the spectrum and vacant that spectrum if PU will reappear to reduce the interference.

In the underlay cognitive network model, the PU and SU can co-exist with each other for spectrum sharing, however a PU is always having a high priority over SU. Furthermore, the PU defined its constraint known as Interference temperature (IT). The third is overlay cognitive networks, in which SUs and PUs exists with each other are allowed to communicate concurrently. The cooperation between PN and SN is granted. However, for data transmission the secondary signal relay on primary network to transmit data.

Spectrum utilization problem [2]-[4], is solved through CR. Due to spectrum's dynamic nature, the CR technology also has to face numerous challenges for quality-of-service **(**QOS). Various range of functions like spectrum sensing, decision, sharing and mobility is related to CR operations. Spectrum sensing (fig.1), is used to check spectrum availability and its parameters, where no PU is present and spectrum holes are easily accessed by SU for transmission. The decision for spectrum access is used to select the best available channel to further enhance the performance of the spectrum. The spectrum sharing means that SU shares the medium in the absence of the PU and vacate the available band if PU reappears to reduce the interference. And at last the SU performs handoff strategy from one frequency band to another is control by spectrum mobility.

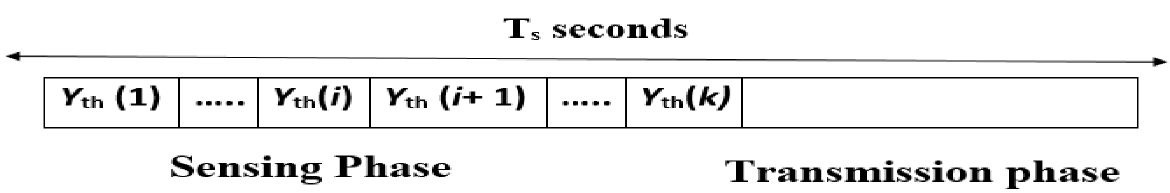

Figure 1: The sensing and transmission phase

In underlay mode the SU is allowed with active PU to access the spectrum but PU sets a pre-defined limit, if SU exceed it results in interference at primary receivers [1]-[5]. A comparison between underlay and Interwave paradigm under the outage probability as shown in Fig.2.

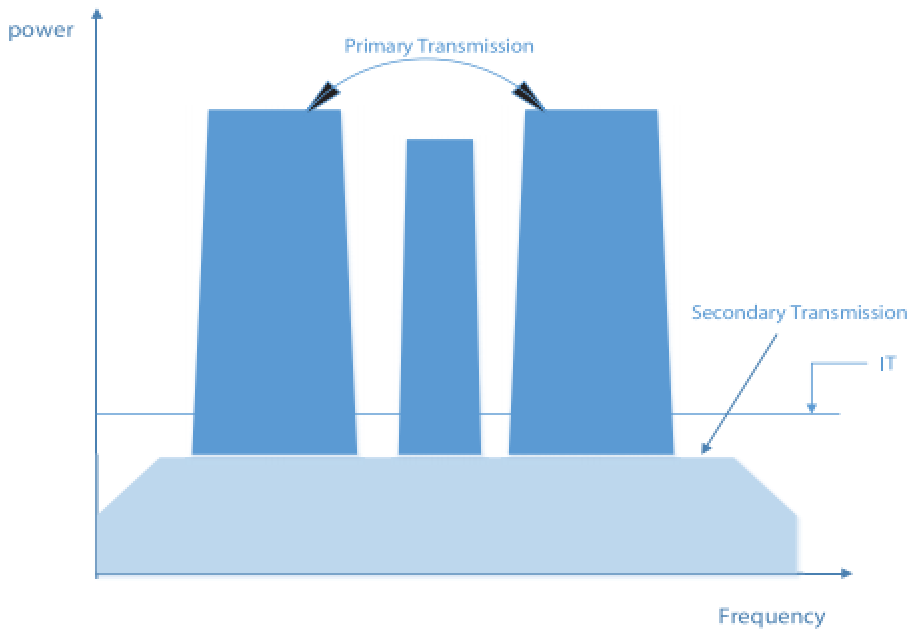

Figure 2: Cognitive underlay mode

In case of multiple channel [1]-[7], the SU finds free channel and start transmitting but with low power by maintaining the interference temperature. Using underlay spectrum sharing access the overall throughput of the system will be increased.

The SU with the best spectrum access allow to use necessary resource efficient algorithm [8], to enhance the performance and to protect the PU. Also, channel state information (CSI) is also known. Resource allocation (RA) strategy uses two different approaches one is centralized and other is distributed. In centralized approach central node collects information and perform measurements and takes final decision to get the optimal decision and minimize the interference, however it causes high signaling overhead and wasteful use of resources. In distributed approach each node performs its measurement to take a decision or shared with its neighbor to make decision. This will reduce the overhead and delay in exchanging the information and increases system flexibility. It is more suitable for small networks.

In underlay cognitive networks, the main criteria are to maximize the throughput by maximizing transmission power minimizing SNIR, QOS constraint, and minimizing interference at PU receiver. It also aims to schedule best user with high priority all the time as compared to weak, which increases the throughput however results in unfairness among users [6]. Interference minimization is another criterion of underlay CRN by focusing on secondary to primary interference. E.g. IT. Generally, two interference constraint are in RA process. The interference hold at each instant is known as short term interference constraint. And if IT is satisfied for fraction of time then it is known as long-term interference constraint. Fairness in RA is also another objective. Generally, for fairness there are two strategies. In order to maximize the worst user throughput, we use max-min fairness. In proportional fairness, RA depends on user's window of past time slots. QOS constraint, e.g., SNIR, time delay, efficient transmission rate is also considered important for efficient communication.

In our proposal, we primarily focus on underlay network model because the existence of SU along with PU is possible but under pre-defined constraint, however the PU is allocated with high priority to access spectrum than SU. Further, the PU has a constraint called as IT. Whenever PU reappears the SU instead of immediately vacating the spectrum starts transmission with low power from available band in order to reduce the interference. In this way resources are efficiently utilized rather than Interwave and underlay mode. In underlay cognitive network SU has to continuously monitor the CSI of the PU channel which results in the wastage of energy and more delay. And in all scheme's the IT is kept constant for all the slots irrespective of PU activity. Most of the schemes focuses on IT limit in order to transmit on a channel along with the PU, paying no attention to the optimal channel selection which incurs extra spectrum sensing overhead while comprising on energy and delay.

1.2 Problem statement

The CR provides solutions for the spectrum utilization problem where spectrum access is dynamic in nature. In underlay mode, a SU is allowed with an active PU to access the spectrum under a pre-defined threshold. In case of multiple channel, the SU will start transmission in available free channels under pre-defined limit in order to increase throughput. In majority of the spectrum sensing techniques, an underlay cognitive network requires a SU to continuously monitor CSI in order to access channel. In all the schemes we, have studied so far IT threshold is usually kept constant for all the slots irrespective of PU's activity. Most of the scheme focuses on IT limit in order to transmit on a channel along with the PU paying no attention to the optimal channel selection which incurs extra spectrum sensing overhead while compromising on energy and delay.

1.3 Motivation

An underlay cognitive networks requires an SU to continuously monitor CSI in order to access channel, and no one has pay attention in the energy consumption while sensing at each slot and IT which is kept constant for all the slots. We plan to propose an efficient spectrum sensing technique, by predicting the optimal time slot to be in used parallel with PU, and to dynamically adjust its IT itself with each slot.

1.4 Thesis Organization

The rest of thesis is organized in following order. In Chapter 2 we described literature review along with critical discussion on existing related techniques. Network model and experiment setup is discussed in chapter 3. Chapter 4 presents performance evaluation and graphs. In chapter 5 presents the conclusion and future work.

Chapter 2

Related Work

In this chapter, we have described the background study on cognitive radio networks using underlay scheme and other schemes. Majority of the schemes focuses on hybrid techniques either using Interwave underlay or underlay overlay schemes. All of this work is in attempt to enhance QoS parameters of cognitive radio network to utilize efficiently the spectrum band. In [9], a queuing model is used to guaranty the QOS for SU's with multiple classes having different services under a non-preemptive priority scheme. A packet scheduling scheme is used for the transmission buffer to differentiate services, where packets with high priority packets are given high priority by using opportunistic scheduling (OS) to minimize average packet transmission rate while maximizing throughput. In the same work, multicast routing (MS) data can be transferred using minimum SNIR to different users. The OS scheme is used for the high priority packet transmission, and low priority packets with MS scheme to increase the spectral efficiency and guaranty fairness. However, physical transmission characteristics and queue waiting time causes end to end delay, fading and interference.

Recently researchers have focused on the active and inactive state of the PU. In hybrid Interwave underlay spectrum [10], access focus is on the on/off states of PU and its operating range which is more difficult due to Non-Gaussian noise. In hybrid Interwave-underlay access, SU can easily switch among Interwave-underlay modes based on PU spectrum sensing results. If PU is absent then it will choose Interwave mode and transmit data with high power. However, if PU is detected then it will easily switch to underlay mode and transmit with low power by maintaining the interference threshold. Two different schemes are used for high order cumulants. Single high-order cumulants (SCSR) with low computational complexity based on sensing and power recognition schemes. The other is High-order cumulants (HCSR) with high computational complexity based on sensing and power recognition schemes to enhance the detection process to achieves good performance and results. However, HCSR compromises between performance and complexity, and this approach is only valid to non-gaussian signal.

Researchers have proposed an energy-harvesting [11], CRN (EH-CRN) mechanism for green energy utilization, where SU having no battery or other source to improves its spectrum utilization. In underlay mode, the harvested energy is used for self-sustainability and also for spectrum sensing. While in Interwave mode it is used for "cooperation" with overlay mode of EH-CRN. The SU use RF signal of PU for harvesting and then start communication with PU in licensed band allocated time. The SU transmission is under pre-defined limit to protect the PU from IT, which causes energy causality and interference power constrained to maximize throughput to gain optimal time and enhance its power allocation. The JOPTA algorithm is used, which transforms whole problem into series of feasible problem and solve them with dual decomposition method to achieve throughput maximization. However, due to super capacitor leakage it causes energy causality problem and it does not considered energy storage and management.

With the increasing growth of mobile devices user's demands become more challenging and to improve the spectral efficiency and user demands D2D communication underlying LTE networks [12], is proposed to utilized the licensed band in the absence of PU. In D2D communication mobile devices established direct link without traversing the base station, and reuse spectrum by controlling the base station to improve the spectrum efficiency. This approach has to face two major challenges; one is opportunistic feature of licensed channel which is solved by duty cycle-based protocol in which BS schedule transmission according to the data demand; the second is sub-channel allocation problem which is solved by swap algorithm with the low complexity. It also minimizes the interference at the Wi-Fi system. However, LTE-U and D2D-U joint interference becomes complicated.

In [13], a hybrid overlay-underlay approach is proposed. The main objective is to maximize throughput by switching among overlay-underlay schemes. There are three states of PU either it is idle, concurrent and busy state, two states for SU either it is idle or transmit. In Markov decision process framework although PU states are hidden, but its activities such as data transfer range and IT are to be known. In overlay scheme, SU becomes idle where PU is in active state. But it should switch to underlay mode and start transmission with low power to maintain IT. The optimal alpha vector is formulated by POMDP problem using incremental pruning algorithm. PLOP requires sensing at first time slot, and CLAP requires sensing only at start and then its ACK information of previous time slot. The ACK/NAV information of precious slots saves energy and time however, PLOP requires sensitive sensing at every time slot so wastage of energy. It optimizes throughput but avoids interference at PU.

The proposed cognitive radio-Opportunistic Splitting Algorithm CR-OSA [14], scheme do not need centralized control to allocate resources to different user. The OSA is used to choose the best user. The main advantage is that this approach is distributed. Each user needs to know their own knowledge about channel gains. Due to channel information, user do not need to verify each other as they can be uniquely identified. It solves centralized scheduler problem. The mutual interference occurrence in between PU and SU is the major difference between OSA and proposed CR-OSA. The CR-OSA consist of two steps; first is to attach each SU to one or more sub-channels called sub-channel attachment; the second step is where each sub-channel is assigned to winner SU called sub-channel assignment. Selecting the best SU improves system throughput with increase in no of users in the system. The simulation has shown less computational complexity effort for limited rate scenario, and it provides higher utilization for maximum rate scenarios. The centralized scheduler increases delay and overhead. However, QOS is not guaranteed.

Nowadays delay and QOS is a major issue. A Hybrid scheme is proposed to guaranty throughput for cognitive users. Performance of PU is improved by using efficient resource algorithm and spectrum sensing can be dynamically adjusted according to PN activities. This scheme [15], divides the two-dimensional plane in to two regions, so SU can dynamically switch between underlay mode having accurate CSI, and overlay mode having inaccurate CSI under given QOS constraint. For optimal transmission strategy two limiting case, are analyzed. First is optimal transmission strategy with loose QOS requirements, whereas in second SU transfers with constant rate with strict QOS requirement. The results show QOS constraint becomes strict when the sensing time for overlay mode increases. However, the channel estimation error is highly vulnerable for underlay mode rather than overlay.

A generalized access strategy (GAS) algorithm [16], is proposed to maximize the throughput in a multichannel CRN by keeping the interference under a certain threshold. There are N licensed channels the SU selects channel for spectrum sensing in sequential order based on its transmission power and channel gain. In transmission phase the SU system access channel based on the result and channel with low probability are accessed directly. The power allocation of SU is optimized to maximize the throughput. Therefore, channel is partitioned in to two subsets. In first NI(NI<N) channels are accessed via hybrid access strategy, and N-N1 channel are accessed via underlay access strategy. By using GAS, the SU system can transmit data efficiently during both idle and occupied periods. The SU has more chances to find an idle channel if channels are sensed sufficiently. Longer sensing time increases accuracy, however it also reduces available time and affect the throughput. Using optimal stop theory, we find the optimal no of sensing channel.

In [17], two novels cooperative mode are deployed for full duplex D2D communication underlying cellular network. The MU-MIMO based mode (N-mode) and sequential forwarding mode (S-mode). These modes are designed to improve the spectral efficiency. In full duplex communication user at the same time transmit and can receive simultaneously and link are assumed to be bi-directional. Various modulation and coding schemes limits the transmission rate of the communication. Therefore, NOMA technique is used. There are two modes: N-mode, and S-mode, and both follow the same idea. In step 1 the data is sent to D2D user, which also receives its own data, it then applies redundant capacity to receive data of cellular data of cellular user. While in step 2 two D2D users manage the data capacity to relay the cellular data to cellular user. When data is received by both, successive interference (SIS) technology is utilized in both steps. However, the processes are different for both modes. In N-mode, two D2D user first exchange the received cellular data in a slot so that both D2D user have cellular data for the cellular user. In next slot these two D2D user conduct multi-user network MIMO to forward cellular data to cellular user to exploit channel diversity. In S-mode two DD user forward the received cellular data to two cellular users sequentially in two slots in order to leverage spatial distribution. In optimal power allocation, the maximum transmission is treated as QOS for both. The spatial and energy efficiency is improved for edge user.

However, due to restricted modulation and coding schemes the transmission rate of each link is limited.

In [18], a hybrid scheme is proposed which considers underlay-Interwave paradigm in which SN switches between interweave-underlay schemes based on whether spectrum holes can be detected. The current CSI is at secondary transmitter and interference channel outdated CSI is at secondary transmitter. A co-relation model is used to handle outdated CSI. It will reduce the capacity of secondary network. This scheme shows a sequential use of paradigm in a cyclic manner, which allows SU to utilize the spectrum holes and avoid any kind of short and long interference limits and if PU is detected, it switches to underlay mode to increase the efficiency of SU. The outdated CSI, mobility, and delay is available to SU, therefore violating peak Interference power constraint. Instead of considering only transmitter they consider multi-user SN and the effect of interference channel from PU to SU in SN the outdated CSI causes both average interference power and the Interference outage constraint (IOC). So, the convex problem is converted in to non-convex, if interference channel current CSI is not available to secondary transmitter in order to maximize SU capacity and maintaining the constraints. Here throughput is high and interference is reduced. However, it is dependent on topology and the distance among PU receiver and SU transmitter.

An orthogonal frequency-division multiplexing (OFDM) [19], technique for efficient power and channel access technique for SU in OFDM based CR networks in which secondary network (SN) is divided in to overlay and hybrid modes. The main approach is to formulate a general problem where multiple SUs spread in a SN, which includes all the spectrum access methods. In general, it is not up-front to decide whether spectrum sensing for each channel is required or not even if the location information is known. Therefore, the focus of their work is on energy efficiency through different test of interference violation to find spectrum or channel that are not participating in the communication and must further avoid un-necessary sensing of those spectrum. On results of interference violation, proposed location-aware design then incorporates location information to access the spectrum adaptively and achieves improved energy efficiency. The power associated with a given data rate should be minimized for energy efficient design. However, the performance highly depends on the network topology and the distance between the SU transmitter and the PU receiver.

The presence of primary network (PN) is always unknown to the SU. Spectrum sensing is needed to detect presence of PU. However, each SU sense limited number of channels due to resource constraint. In [20], a game theoretic approach is proposed, in which SU learns the presence of PU and the access to the channel among M-SU. The policy is based on two distributed learning schemes. In the first scheme, the SU learns the channel with high and low usability, and it prevents sensing high usable channels for that upper confidence bound (UCB) learning, which is used by SU to check the mean availability of primary channel. In second scheme, the SU learns from its collision domain from its previous history using stochastic learning automata (SLA), the SU learns from its channel selection series and its collision inside the network. The distributed channel selection & access problem is a non-cooperative strategic game. Because due to exact potential games it may have a strategy for Nash Equilibrium (NE). The authors have proved that channel access policies have good results, and it is also more energy efficient and high throughput. However, fairness among SU's is not considered. And ensuring fairness among distributed protocol design is challenging.

Table 1: Comparison of different underlay techniques in CRNs

Sr. No.	**Technique or Scheme**	**Algorithm or Model**	**Brief Description**	**Advantages**	**Limitations**
1	Hybrid Interwave-Underlay scheme 2018 [9]	SCSR model HCSR model	SCSR is for low computational complexity by leveraging minimum spectrum bays risk criterion by short sensing period. HCSR for multiple order and timely to future improve detection.	It is very fast to noise variance ambiguity. It extracts non-Gaussian noise form Gaussian noise.	The HCSR compromises between performance and complexity. This approach is only valid to non-Gaussian signal.
2	Hybrid transmission scheduling scheme	G1/G/1 Queue model	A scheme where the transmission of high priority packets is through OS scheme and low priority packets using MS scheme.	Increases spectral efficiency and the fairness among users.	Physical transmission characteristics and queue waiting time causes end to end

	2018 [10]			.	delay. Fading and interference.
3	Energy harvesting framework 2017 [11]	JOPTA algorithm	To lower the transmission power of SU by multi-hop transmission with TDMA.	PU RF signals bear no interference due to strict restriction on SU.	Energy causality problem due to super capacitor leakage. .
4	D2D underlay scheme 2017 [12]	Sensing protocol Swap algorithm	Spectrum efficiency is improved to solve sub-channel allocation problem.	Interference among both users is reduced.	The Mutual interference among LTE-U and D2D-U unlicensed communication becomes complicated.
5	Markov decision process framework 2014 [13]	Incremental pruning algorithm	Hybrid overlay underlay is used to efficiently utilized spectrum for optimal channel access and power adaption.	The ACK/NAV info of previous slots saves energy & time. Switching between overlay & underlay. improves spectrum efficiency.	PLOP requires sensitive sensing at every time slot so wastage of energy.
6	OSA distributed scheme 2014 [14]	CR-OSA	To allocate SU sub-channels whose desired link gain are maximum but considering interference constraint to reduce delay and overhead.	Maximize throughput Reduce delay and overhead.	QOS is not guaranteed.
7	Hybrid underlay-overlay scheme 2014 [15]	Effective capacity Theory	A Hybrid scheme in which CR user’s QOS is guaranteed & network throughput is improved.	Provide better statistical delay QOS.	The channel estimation error is highly vulnerable for underlay mode rather than overlay.
8	Two phase optimization frameworks	GAS algorithm Convex	A GAS strategy in a multi-channel CRN for sensing spectrum & perform channel	Throughput is high. In optimal stopping rule provide low	Longer sensing increases sensing accuracy but causes

	2016 [16]	algorithm	selection, sensing time allocation & power allocation to maximize throughput.	computational complexity.	delay.
9	Novel cooperate D2D mode 2017 [17]	MU+ MIMO based (N mode) Sequential forwarding mode (S-mode)	A cooperate D2D scheme to achieve channel proximity and reuse gain with full duplex technique.	Spatial efficiency improved. High energy efficient for edge users.	Transmission rate becomes limited due to restricted modulation and coding schemes.
10	Hybrid Underlay Interwave Scheme 2015 [18]	Correlation model Interference outage probability constraint (IOPC)	Sequential use of both model in a cyclic manner to increase SU capacity.	Throughput is high. Interference is reduced.	Outdated CSI limits capacity. Accurate spectrum sensing adds complexity.
11	Adaptive hybrid resource allocation scheme 2015 [19]	Novel adaptive power algorithm Channel allocation algorithm	A scheme where SU choose any spectrum access technique to optimize the channel allocation and its power but it is location dependent.	Minimize power consumption Avoids un-necessary spectrum sensing	Dependent on network topology. Depends on distance.
12	Game theoretic approach 2016 [20]	Stochastic learning automata. UCB based learning	Each SU will choose the available best channel based on its probability value and which updates periodically based on its collision events.	High QOS Throughput is high	Fairness among SU's is challenging.

Chapter 3

DI-AIT

Design and Operation

3.1 Introduction

In this chapter, we propose an efficient scheme called "Distributed intelligent channel access with adaptive IT (DI-AIT)" to solve the spectrum utilization problem. The proposed scheme is robust under different traffic patterns. This chapter elaborate design & operations of DI-AIT, the network model and algorithms. The chapter is further organized as follows: The motivation for solution is described in section 3.2. Network model used in our proposed scheme is discussed in section 3.3. Section 3.4 comprehensively explain the operation related to proposed scheme. The learning-based spectrum sensing technique is used in section 3.5. Rest of the chapter contains algorithms used in our proposed scheme with their explanation.

3.2 Motivation

While comparing different techniques and methods for underlay spectrum sensing in cognitive radio network (Table-1) researchers have consider their work with respect to interference, complexity, QOS, and other metrics. In [9], M. EI et al. proposed a scheduling scheme to obtain spectral efficiency and guaranty fairness. However, physical transmission characteristics and queue waiting time causes end to end delay, fading, and interference. In [10], A. Ali et al. proposed a scheme to lower the transmission power of SU by multi-hop transmission. The major issue is energy causality problem due to super capacitor leakage. In [12], A. Karmokar et al. proposed a scheme to efficiently utilized the spectrum for optimal channel access and power adaption however, PLOP requires sensitive sensing at every time slot cause wastage of energy. In [13], M. Tanab et al. proposed a scheme to minimize delay and overhead by allocating the SU sub-channels however, its QOS is not guaranteed. In [14], Y. Wang et al. proposed a scheme where throughput will be compressed but it is guaranteed that its QOS requirement will be higher. In this scheme, the channel estimation error is highly vulnerable for underlay mode. In [15], C. Yang et al. proposed a scheme to perform channel selection, sensing time adjustment and power allocation. This scheme requires, longer sensing which results in significant delay.

In underlay cognitive radio networks, an SU is allowed with active PU to access the spectrum under a pre-defined threshold. In case of multi-channel, the SU will start transmission in available free channels under pre-defined limit to increase the throughput. In underlay cognitive networks requires the SU to continuously monitor CSI in order to access channel, which results in higher delay, and energy consumption. We plan to purpose an efficient spectrum sensing technique by predicting the future idle time of primary user's activity in a cognitive underlay radio network based on machine learning.

3.3 Network model:

In underlay scheme SU access the spectrum along with PU, interference on primary side receiver is on certain limit known as interference temperature. The use of efficient algorithm is necessary to provide SU with best spectrum access as well as performance is improved and PU is protected. Also, CSI of both links should also be known and maintained.

3.3.1 Distributed scheme

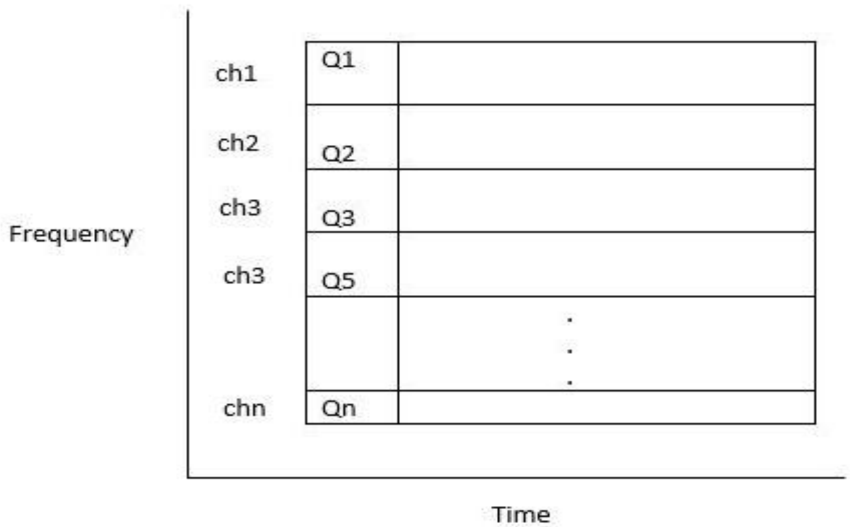

Figure 3: The proposed DI-AIT technique

3.4 Preliminaries:

In our proposed scheme we consider SU in a multi-channel CRN. A slotted primary network (PN) of X radio channel, Y SUs for a SN which is in searching to choose the best idle channel in the PN in (Table-2). We assume the scenario in which $Y < X$ in which no of primary channel are larger than secondary channel. Also, we will consider scenario where $Y \geq X$ however, $Y < X$ is more challenging for efficient access to maximize SU throughput and n is the current time slot.

Table 2: Notations of different parameters

Symbol	Description
X	No of primary users
Y	No of secondary users
N	Current time slot *i*
Zi(n)	Primary channel availability at timeslot *n*
IT	Interference temperature to protect PU from interference due to SU
A	Learning rate
R	Reward value which is updated with each channel access

Let *Zi(n*) denotes availability of channel state i in PN on a time-slot n, in which if channel is available them *Zi(n)* is *1* else *0*. We assume that all SU's are active to send and are in search to access optimal channels. We are focusing on scenario in which SU sense all the channel and maintain a Q-table which contains the Q-values of all the available channels based on Q-value. Next time in order get other channels it will directly select the channel without sensing based on its Q-table values [23]. In this thesis we assume perfect spectrum sensing for all SU's. We assume that SU sense channel access it in a given time slot specifically due to hardware limitations.

In our proposed scheme each SU learns the mean availability of the primary channel α over time based on its spectrum sensing results and its observation history. The mean availability learning rate is *1* if it gets the channel otherwise it is *0.* If SU's access same channel, collision occurs resulting in zero throughput. And the Q-table is updated depending on the traffic pattern. If traffic pattern changes rapidly then short interval of time Q-table is also updated. And if traffic patterns are uniform for a long period then Q-table is updated after a specific time period [22]. The reward value is represented by *r* and its value is incremented by 1 in case of successful channel access and in case of failure it is always decremented by 1.

In previous work the interference temperature (IT) is usually kept constant for SU transmission and reception but know we have made to adjust IT dynamically based on its PU transmission power. And to dynamically adjust IT for each channel, we have considered three IT values. Which dynamically adjusted based on its Q-values. Through this the throughput of the system increases.

3.5 Learning based spectrum sensing

In this scheme we will be able to learn the spectrum access method and different traffic patterns which changes due to dynamic nature of the spectrum through Q-learning techniques.

3.5.1 Q-learning model

In our proposed scheme we use Q-learning to allow SU to access the PU channel. Request if fulfilled through learning-based mechanism. Decision to choose slots is based on learning rewards value of available slots. We apply Q-learning technique [21] at the PU, from where the actions are based on thee Q-function. The Q-value of the slot tells us about the quality of slot. The actions on PU slot is either it is available or not. The Q-value is updates on each action as.

$$Q(t+1) = Qt\ (i, k) + \alpha\ (r - Qt\ (i, k)) \qquad (1)$$

Where $Q(t+1)$ is PU current value, action upon which is taken, and *"i"* is the SU and k is the PU timeslot where r is reward value, α stands for learning rate. To get the maximum Q-value in every next slot and updates the current Q-value and learning rate $0< \alpha <1$ is used to speed the process learning.

In reinforcement learning actions leads from one state to another state [24]. An agent receives an input of current state than choose an action across input and generates output which will be the input for other state. To maximize the reward an agent is used. The following elements are in proposed scheme.

Agent: In our proposed scheme an SU acts an agent containing information about network.

Action: action in our scheme is to select or reject the channel.

Reward: it shows that SU is allocated channel or not and it is incremented for each success and decremented in case of failure.

3.5.2 Distributed intelligent channel access with adaptive IT (DI-AIT)

3.5.2.1 Algorithm 1: Training Phase

In our proposed solution we will initiate a training phase in which we make SU to learn about PU presence inside the channel so, we first initiate a learning process in which we consider all PU time slots and SU starts spectrum sensing and maintain a Q-table for itself and we have to fine a time slot with highest Q-value for each PU. If a channel is selected then it will increment its reward value by 1 otherwise 0. And this table is updated after different intervals of time. If traffic patterns have high mobility then this Q-table is updated regularly. And if traffic mobility is uniform then Q-table is updated for specific period of time. And after maintaining the Q-table the SU now will be able to choose any other channel depending on its Q-value. It will increase throughput of the spectrum and results in decrease in delay and it will also save energy and cause minimum interference for the transmission of PU and SU.

Algorithm:

Input: All PU's time slots, T_p

Output: A time slot with highest Q-value for each PU denoted as MAP_t $\{PU_{id}, T_p\}$

Step 1 Repeat for M episodes

Step 2 In each episode

While ($T_p \neq \phi$)

  Select a time slot t_n € T_p

    Calculate SNR of t_n

      If (SNR > threshold)

        Add 1 in the reward value

      If (SNR < threshold)

        Decrement 1 in the reward value

Step 3 Update the value of reward according to

$$Q(t+1) = Qt(i, k) + \alpha (r - Qt(i, k))$$

Step 4 End While

Step 5 End episodes

3.5.2.2 Algorithm 2: Adaptive Channel Access

Once Q-table is maintained the next step is to choose the best available channel. The SU now choose the best available any channel with highest Q-value. And to transmit data with high transmission power.

Algorithm:

Input: Previous slots with Q-value from all PU's

Output: A T_p, i.e. Selected time slot

Step 1 While (MAP≠ ϕ)

Step 2 Select the slots with highest Q-value denoted as T_p, i.e. preferred time slot

Step 3 End While

Step 4 Update the IT according to T_p, using algorithm 3

3.5.2.3 Algorithm 3: Interference Temperature

Once the Q-table is maintained by SU, then SU will choose channel with highest Q-value form the available Q-table. Now SU will start transmission according to PU defined constraint called interference temperature (IT). In previous work the IT is usually kept constant for SU transmission and reception but know we have made it to adjust its IT dynamically based on its PU transmission power which may be different for all the available channel. And to dynamically adjust IT for each channel, we have considered three different IT values, highest, medium and low. Which dynamically adjusted based on its Q-values. Through this the throughput of the system increases.

Algorithm:

Input: Time-slot T_p, with Q-value

Step 1 If (Q-value >= highest)

Set IT with IT+4

Step 2 If (Q-value <= low)

Set IT to default

Step 3 If (Q-value > low && Q-value < medium)

Set IT with IT+2

Chapter 4

Results and Analysis

4.1 Experimental setup

In this chapter, detailed simulation analysis and performance evaluation for DI-AIT scheme is discussed and compared with CogNS and GAS schemes is discussed to observe the change due to movement of PU and SU which are affecting the overall capability of the system. All the simulations have been conducted using Ns-2 and MATLAB. Various performance metrics and trails have been taken in order to find throughput, bit error rate and blocking probability of the system.

4.1.1 Simulation parameters

We simulate DI-AIT scheme by using the parameters defined in Table 3.

Table 3: Simulation parameters

Parameter	**Value/type**
Network area	500 × 500 m2
Nodes no	35
Nodes spatial distribution	Uniform random distribution
Wireless channels	11
Bandwidth of channel	2 Mbps
Propagation model	Two-ray ground
Radio transceivers per node	1
Sensing time	0.025 sec
Operating time	0.6 sec
Hand-off time	0.001 sec
Routing protocol	Dynamic Source Routing
Queue management strategy	Drop tail
TCP connections number	13
Traffic type	Constant Bit Rate, 256kbps rate
Simulation time	100 sec
No of PU’s	10
No of SU’s	25
Sensing time	1.13 ms
Interference temperature	1.5 watt

4.1.2 Performance metrics

Following metrics are used for evaluation of different schemes.

- **Throughput**

  Throughput is the maximum rate of production or item passing through a system or a process. But in networking scenario it is the rate of successful delivery of any message or media over some communication channel. In underlay cognitive radio network as both the PU and SU are allowed to communicate concurrently. And PU always have a high priority to send data then SU so its throughput will always be high than SU. And SU will have a low priority and have low throughput than PU because of the interference threshold value.

- **Bit error rate**

  The rate of errors occur in any transmission system is called bit error rate. It means the total no of errors divided by total no of bit. If medium for transmission and reception is good and signal to noise ratio is low, then the possibility of bit error rate is very low. However, if signal to noise ratio is high and medium is bad then the probability of bit error rate is very high.

- **Blocking probability**

  The evaluation of different services in any medium is known as blocking probability. Higher blocking probability means medium is busy but, lower blocking probability means medium is free. Due to lack of resources the blocking probability will occur. It is measured in Erlang. A blocking probability of 0.01 means 1% of customers will be denied service.

4.1.3 Scenario Description:

- **Scenario 1**

<u>What will be the effect of increase in no of channels on performance metrics? Take averages of 25 trials.</u>

The increase in no of channel also have influence on the performance metrics. In CogNS, the increase in channel means the throughput will be high, bit error rate will be low and blocking probability will also be low. Now if PU reappears then SU has more channel to select and transmit data through these channels. In GAS scheme, the increase in channel means the throughput is high, bit error rate will be low and blocking probability will also be low. SU has more channel to select and transmit data. In DI-AIT increase in channel means the throughput is highest, bit error rate will be lowest and blocking probability will also be lowest. Increase in channels means SU will learn more about channels having low probability of PU's and maintains a Q-table. Now SU will select the channel having the lowest probability of PU. Hence the performance of overall system will increase.

- **Scenario 2**

What will be the effect of SU's on the performance metrics? Take averages of 25 trials.

The performance metrics effects on SU performance. In CogNS scheme the SU throughput is low, bit error rate is high and blocking probability is also high. Because, if PU reappears in the transmission than the SU has to handoff to some other channel which will take extra time, energy, spectrum sensing and delay. And their might me another probability that SU will not find any other channel to continue its transmission hence it has to then abort its transmission hence waste of energy, delay, extra spectrum sensing, less throughput. But in GAS scheme, the SU throughput is high, bit error rate is low and blocking probability is low. Because, the SU and PU are allowed to communicate concurrently but SU has to carry its transmission under a pre-defined threshold value for not causing interference to PU transmission hence its throughput is slightly higher than CogNS scheme. But in proposed DI-AIT scheme, the SU throughput is highest, bit error rate is lowest and blocking probability is also lowest. Because, the SU first learn the spectrum and maintains a Q-table about the activity of PU. And when SU has to send data it will choose a slot with highest Q-value and starts its transmission with high power. And the Q-table is updated according to change in traffic patterns.

- **Scenario 3**

What will be effect of PU's on performance metrics? Take averages of 25 trials.

The PU will also not much effect on performance metrics. Because PU is the licensed user and it always gets the channel whenever it wants. It always has a high priority than SU. It's the SU who have to compete to get the channel it will do spectrum sensing to get the channel to starts its transmission, and if PU will reappear then it will have to have to either handoff to some other channel or to lower its transmission power for not causing interference to PU. In CogNS scheme the PU has same throughput, and highest bit error rate and highest blocking probability due to handoff of SU in case of PU re-appearance. In GAS scheme, the PU has same throughput, lower bit error rate and lower blocking probability due to co-existence of PU and SU. In DI-AIT, the PU has same throughput, lowest bit error rate and lowest blocking probability due to Q-learning applied on this scheme.

4.2 Results and discussions

The PU throughput in CogNS scheme is same because a SU has to sense a channel in which PU is not present and if it is free then it will get the channel and starts its transmission, but if PU will reappear then SU will have to handoff to some other channel. But there might be probability that SU will not get channel thus degrading the PU transmission. But in GAS and DI-AIT the PU will always have a same priority than SU. If SU gets the channel and PU will reappears then SU will not abort its transmission rather it will continue its transmission with pre-defined threshold value known as interference temperature. That's why PU throughput is approximately same in all scenarios.

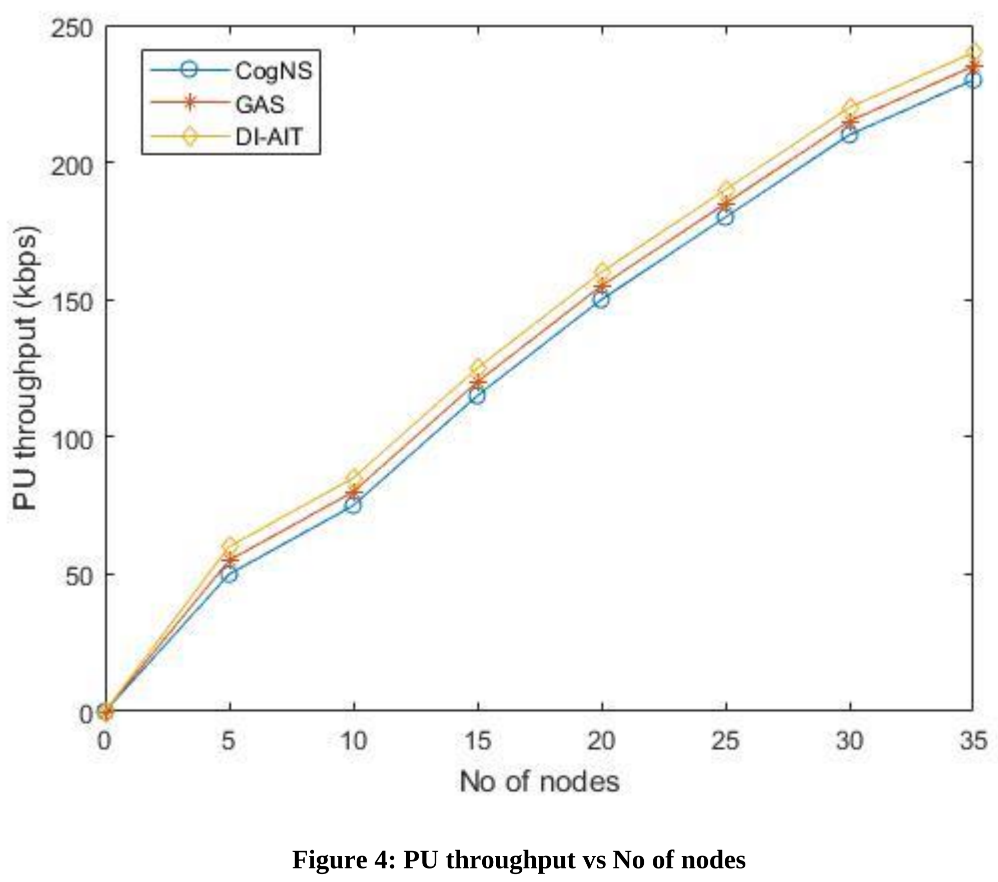

Figure 4: PU throughput vs No of nodes

The PU throughput in CogNS scheme is same with increase in packet per second. With increase in packet per second means SU will take more time to transmit more no of packets per second and it will increase the chances of PU to reappear to continue its transmission again and because a SU has to sense a channel in which PU is not present and if it is free then it will get the channel and starts its transmission, but if PU will reappear then SU will have to handoff to some other channel. But there might be probability that SU will not get channel thus degrading the PU transmission. But in GAS and DI-AIT the PU will always have a same priority because the PU and SU and co-exist with each other and continue their transmission concurrently. If SU gets the channel and PU will reappears then SU will not abort its transmission rather it will continue its transmission with pre-defined threshold value. Hence the PU throughput for GAS and DI-AIT is almost same.

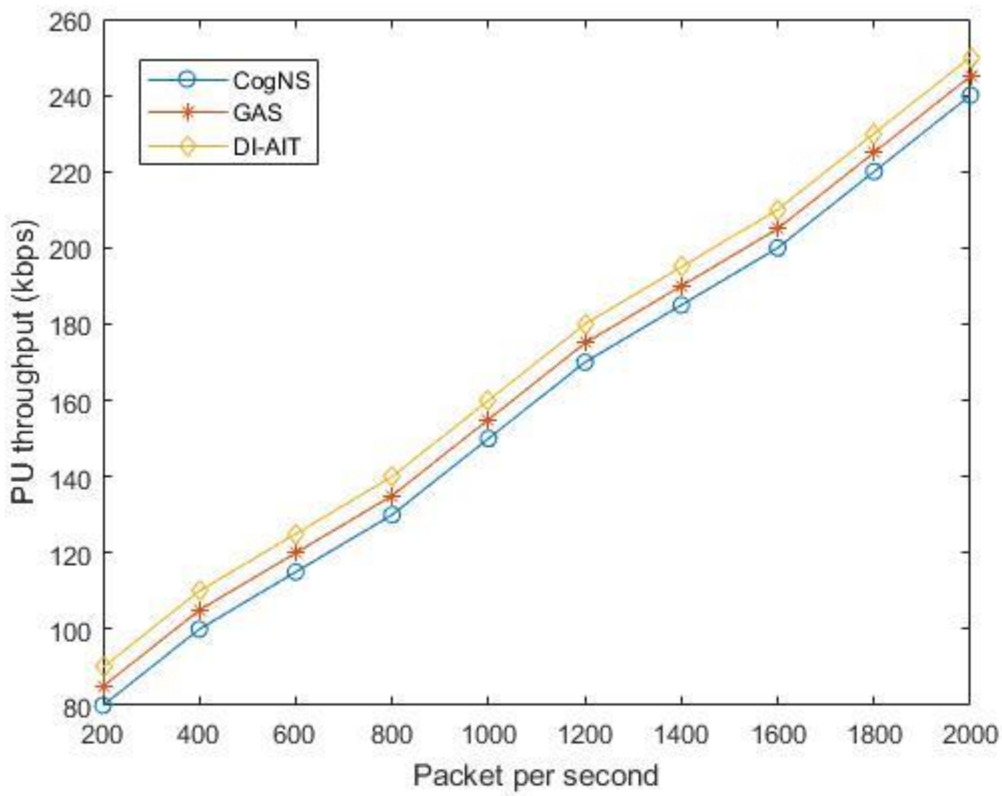

Figure 5: PU throughput vs Packet per second

The PU throughput will be same with increase in simulation time. In CogNS scheme the PU throughput is low and longer simulation time means the SU takes a long time to complete its transmission and chances of PU to appear will be high and because a SU has to sense a channel in which PU is not present and if it is free then it will get the channel and starts its transmission, but if PU will reappear then SU will have to handoff to some other channel. But there might be probability that SU will not get channel thus degrading the PU transmission. But in GAS and DI-AIT the PU will always have a high priority than SU. If SU gets the channel and PU will reappears then SU will not abort its transmission rather it will continue its transmission with pre-defined threshold value known as interference temperature. So, with increase in simulation time the PU throughput is same in case of CogNS because the probability of PU to appear is high, but in GAS and DI-AIT scheme it is almost same due to co-existence of PU and SU under a pre-defined threshold. And PU will always have a high priority and it will always get the channel.

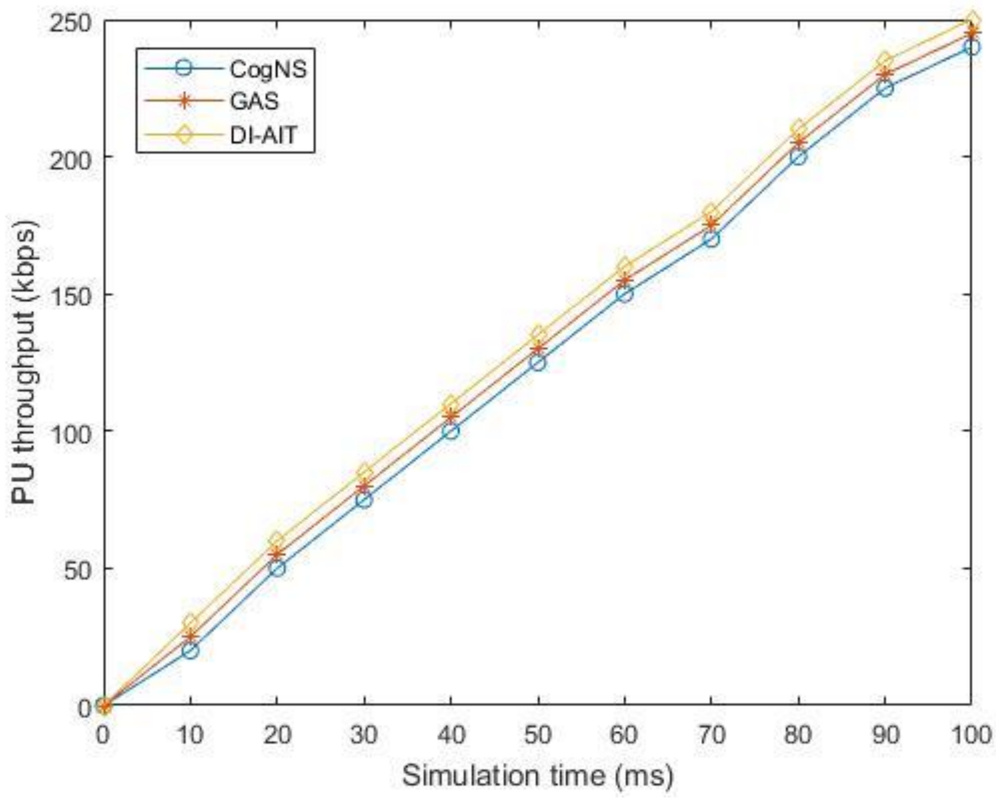

Figure 6: PU throughput vs Simulation time

- **SU throughput**

The SU has always have to first sense the channel and if it is free then it will use that channel to start its transmission but if PU will reappear then it will have to lower its transmission power under pre-defined threshold value which is known as interference temperature. So, in GAS scheme the SU throughput will increase, but PU throughput will always be having a high priority. In CogNS the SU will sense the channel and if it is free then it will start its transmission, but if PU reappears then it will have to handoff to some other channel which will take more time and that's why SU throughput is low here and chances are high it will disrupt PU transmission. But in GAS scheme the SU first sense the channel if it is free then it will start its transmission, but if PU will reappear then it will lower its transmission power under pre-defined threshold value without disrupting the PU transmission that's why its throughput is high with increase in no if nodes than CogNS. But in DI-AIT scheme the SU will first sense the channel and maintain a Q-table of all the available slots. Then if SU has to start transmission it will directly select a channel from a list of available channels and start transmission without sensing it, and start transmission with high power to get higher throughput other than previous two schemes. At start both GAS and DI-AIT have approximately same SU throughput but with time due to Q-learning the throughput of SU in proposed DI-AIT scheme will sufficiently increases.

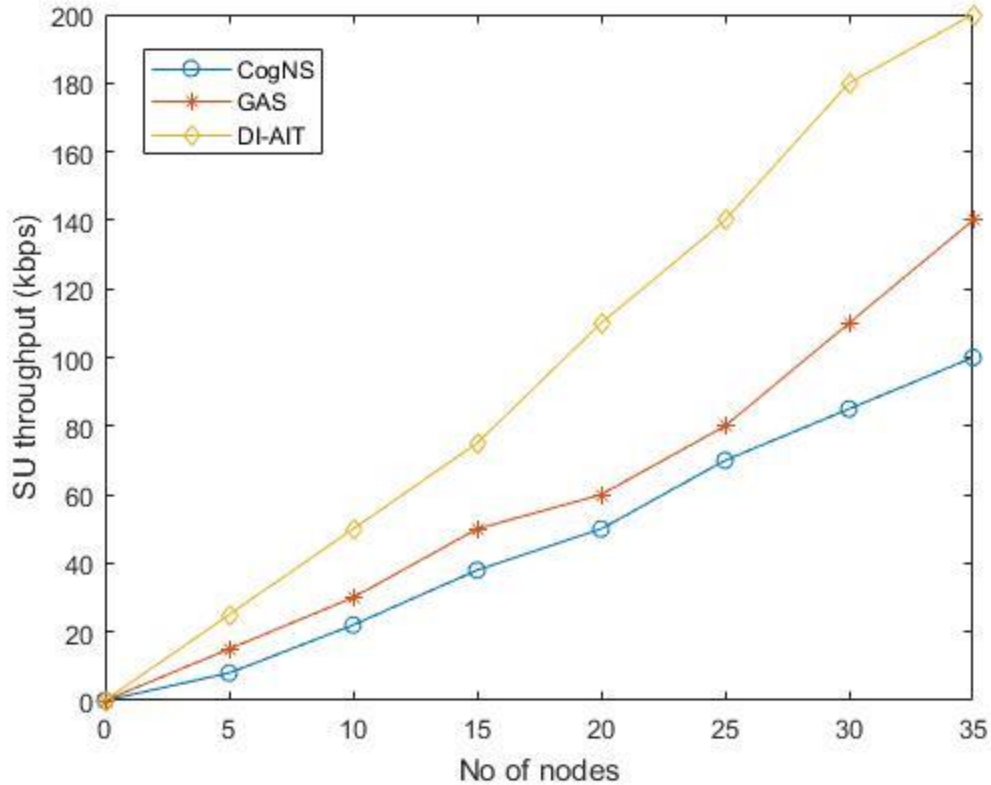

Figure 7: SU throughput vs No of nodes

The SU throughput has a great influence on with the increase in packet per second**.** In CogNS the SU throughput is low because of its handoff strategy in case of PU to appear for its transmission. And will have to sense channel which cause more and more delay, waste of energy and lower the throughput of the system. But in GAS scheme the SU throughput is high because now SU do not have to handoff if PU will reappear in future. Rather it will continue its transmission along with PU but with low transmission power under pre-defined threshold value. In proposed DI-AIT scheme SU will sense the channel and maintains a Q-table and now SU will select the channel based on Q-value from the table where the probability of PU is less and the channel with highest Q-value. So, its SU throughput is very high than previous two schemes. At start both GAS and DI-AIT have approximately same SU throughput but with time due to Q-learning the throughput of SU in proposed DI-AIT scheme will sufficiently increases.

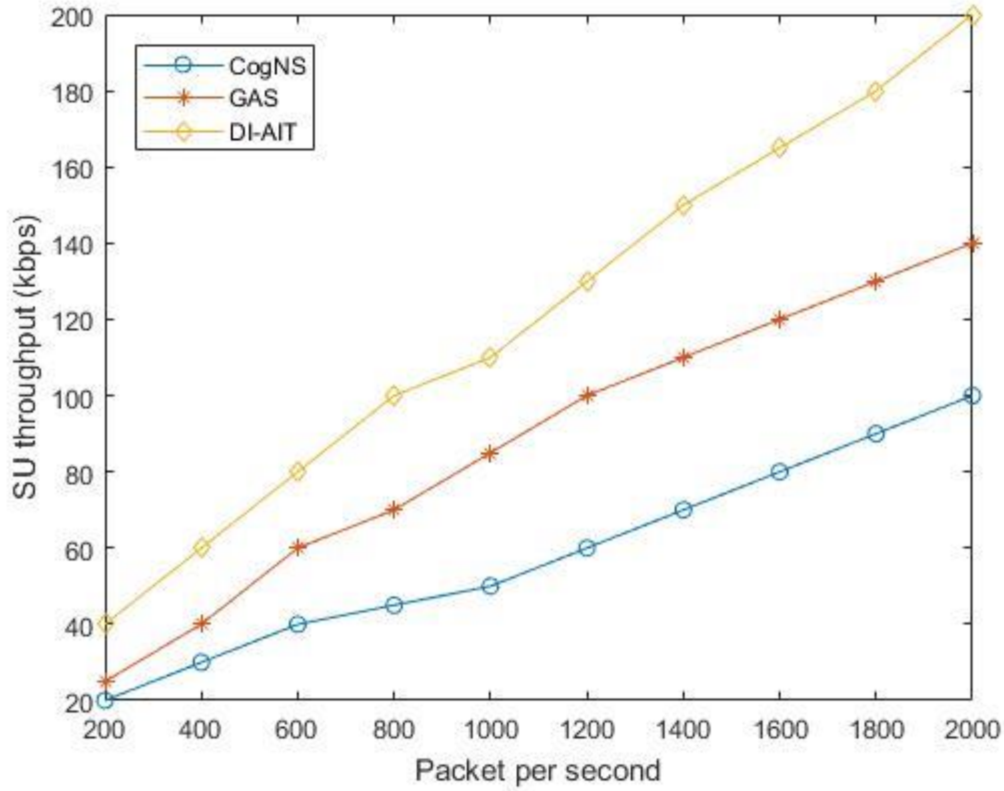

Figure 8: SU throughput vs Packet per second

The SU throughput has also a greater influence on simulation time. With increase in time its throughput will also increase or decrease. In CogNS with increase in simulation time its SU throughput is lower because with increase in time the probability of PU to reappear is high and then it will have to handoff to another channel thus degrading the throughput. In GAS scheme, if the PU will reappear then will not abort its transmission rather lower its transmission power so that's why its throughput is higher than CogNS. But in DI-AIT scheme due to Q-learning and with increase in simulation time the SU has learned a lot about the probability of PU in using the channel. Therefore, it will select the slot in which the probability of PU is low and SU will selects it and start transmission with high power so its throughput is much higher than previous two schemes. At start both GAS and DI-AIT have approximately same SU throughput but with time due to Q-learning the throughput of SU in proposed DI-AIT scheme will sufficiently increases.

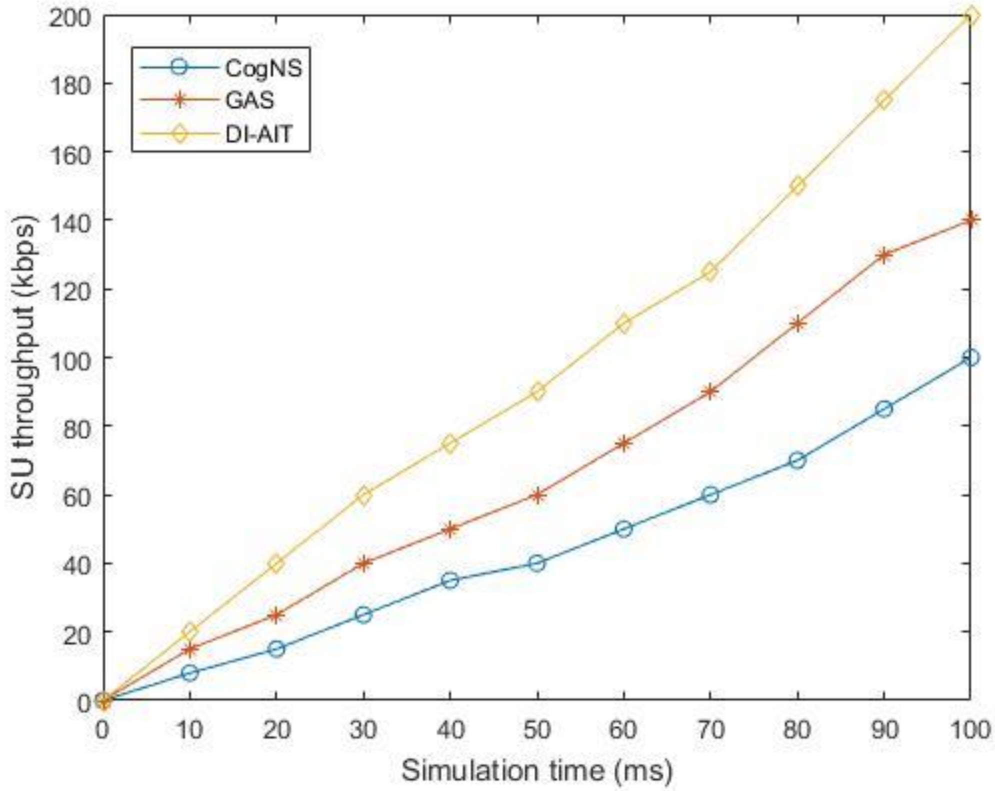

Figure 9: SU throughput vs Simulation time

The bit error rate also varies with the increase in the no of nodes. In CogNS scheme the probability of bit error rate is high because due to increase in no of nodes because when SU will sense the channel in which PU is not present but, when it starts its transmission it will know that the PU is already using the channel. This is call probability of false detection and selection. It will be high due to increase in no of nodes. In case of GAS scheme, the bit error rate will be low because if SU has selected the channel and PU will reappears then SU have to carry its transmission with lower transmission rate due to pre-defined threshold value. It will cause error but lower than CogNS. In DI-AIT scheme it will be lowest due to Q-learning applied which will make the user to learn about the whole spectrum and choose the best available slot in with the probability of PU to re-appear is lowest. Hence the bit error rate will be lowest and throughput is high. At the start the bit error rate is approximately same for GAS and DI-AIT but with time it will be lowest for DI-AIT scheme due to Q-learning applied on this scheme to make this scheme more and more efficient.

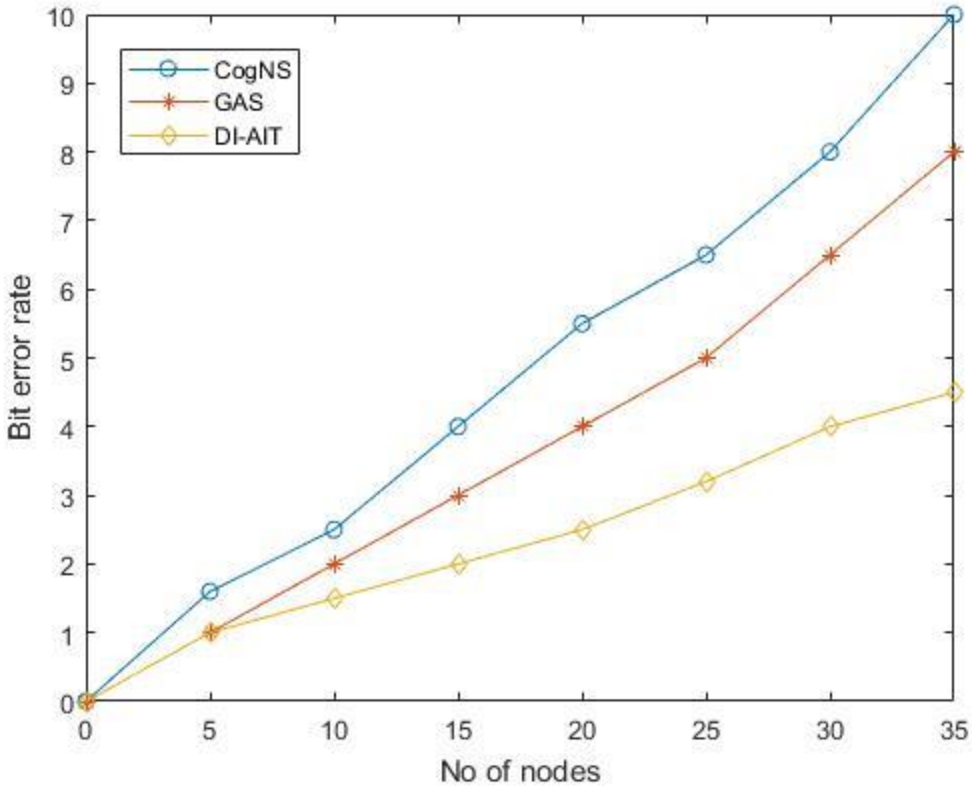

Figure 10: Bit error rate vs No of nodes

The bit error rate also varies with the increase in the packet per second. In CogNS scheme the probability of bit error is high because due to increase in packet per second. Because SU is not allowed to carry its transmission along with PU. With the increase in packet per second the chances of PU to reappears will be high hence SU need to do then handoff to some other channel through spectrum sensing, hence degrading throughput, delay. But the bit error rate in GAS scheme is slightly lower than CogNS because SU and PU are allowed to carry there transmission simultaneously. But SU have to carry its transmission with lower transmission rate. In DI-AIT the bit error rate be lowest due to Q-learning the SU with time will learn maximum the spectrum about the traffic pattern used by PU and maintains a Q-table for SU to select the best slot in which the probability of PU is lowest and carry its transmission with higher transmission rate. But at the start the bit error rate is approximately same for GAS and DI-AIT but with time it will be lowest for DI-AIT scheme due to Q-learning.

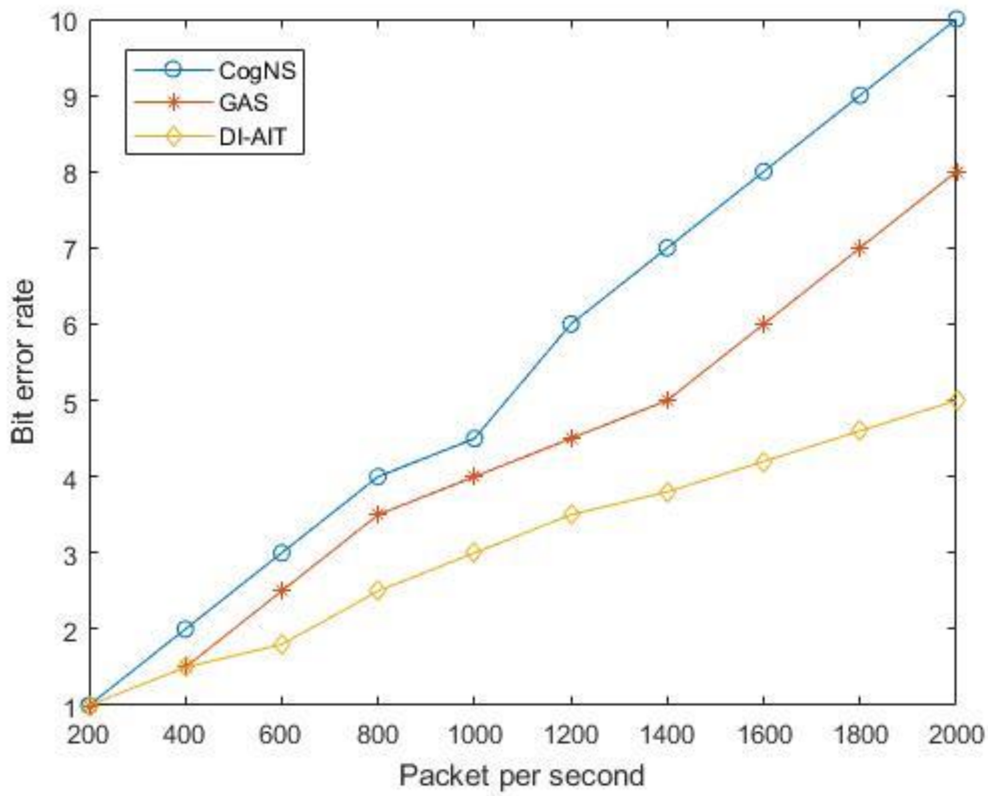

Figure 11: Bit error rate vs Packet per second

The bit error rate also varies with the increase in the simulation time. In CogNS scheme the probability of bit error is high because due to increase in simulation time. Due to increase in the chances of PU to reappear will be high although we have selected the best channel for our transmission. It will affect the transmission of SU automatically in terms of throughput, delay, waste of energy. But in GAS scheme the bit error rate with increase in simulation time is low. If PU will reappear it will not abort its transmission rather continue its transmission with lower transmission power. In case of proposed scheme DI-AIT the bit error rate will be the lowest because due to Q-learning the SU will select the best available slot in which the probability of PU to use this channel is very low and SU will select it to continue its transmission with a high transmission rate thus increasing throughput. But at the start the bit error rate is approximately same for GAS and DI-AIT but with time it will be lowest for DI-AIT scheme due to Q-learning applied to make this scheme efficient.

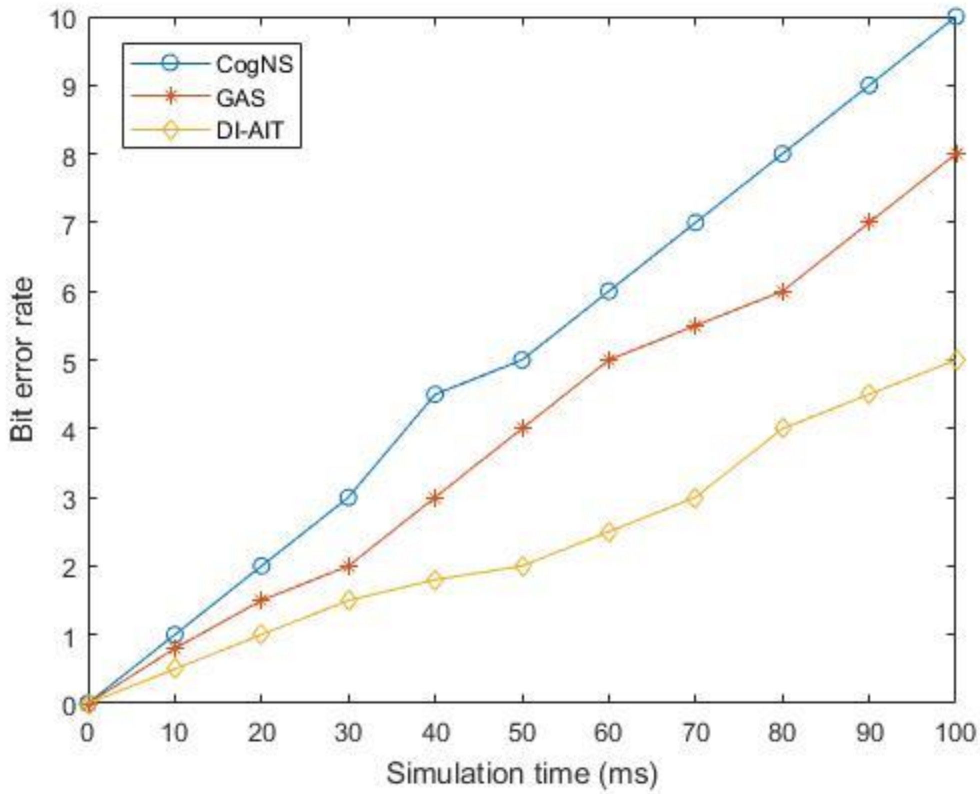

Figure 12: Bit error rate vs Simulation time

The SU blocking probability varies in every scheme. In CogNS the blocking probability will be high because SU has to first sense the channel and if it is available then select it and starts its transmission, but if PU reappear then it has to handoff to other channel but there might be chance that it will not find any channel due to increase in no of nodes. Hence its blocking probability will be high. But in GAS scheme when SU selects the channel after sensing it then it will start its transmission but if PU will reappear then they do not abort its transmission rather lower the transmission power and communicate concurrently hence their blocking probability will be low. But in DI-AIT scheme the SU will first sense the channel and then maintains a Q-table of available slots. The SU now select the channel with highest Q-value and starts its transmission because it has the highest probability that PU will not use this channel for transmission. Hence, the SU blocking probability will be lowest among these three schemes. In the beginning the blocking probability for GAS and DI-AIT scheme is same but due to Q-learning it will be lowest for proposed scheme DI-AIT to increase the efficiency of SU.

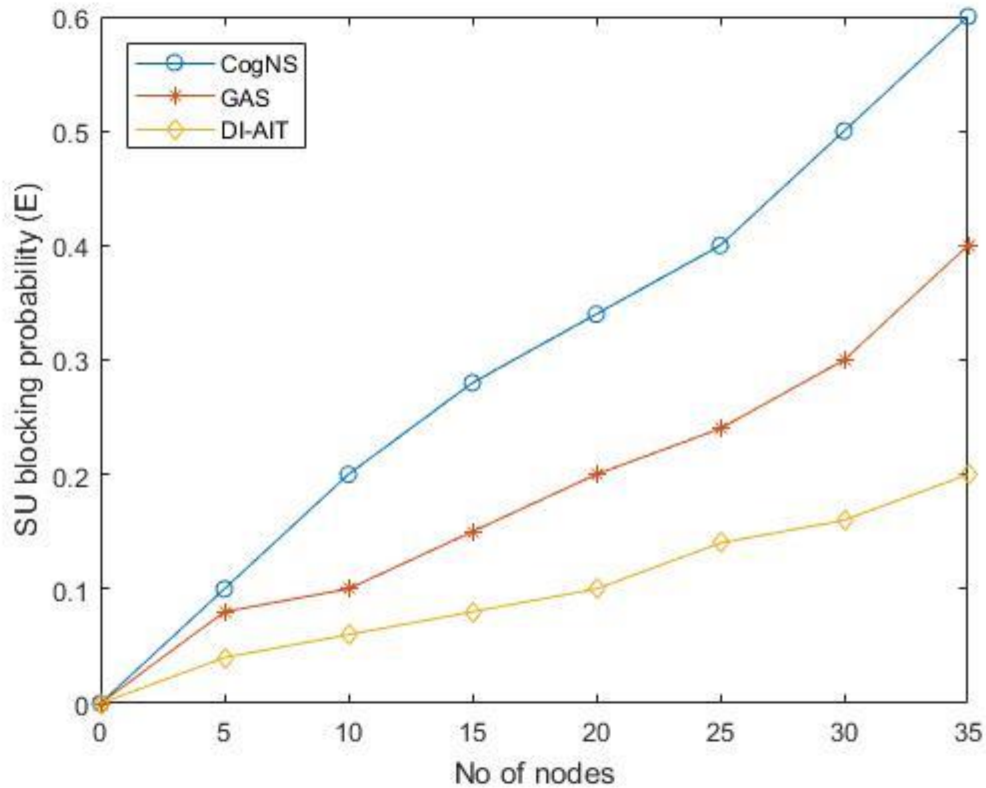

Figure 13: SU Blocking probability vs No of nodes

The SU blocking probability also varies with increase in packet per second. As mentioned in the graph it will lowest for our proposed scheme. Increase in packet per second means SU take longer time to complete its transmission. In CogNS the SU blocking probability is high with increase in packet per second the blocking probability of SU will be high due to its hand off strategy due to reappearing of PU to start its transmission again. It will automatically degrade the performance. But in GAS scheme it will be slightly lower than CogNS due to its concurrent transmission with PU but with lower transmission power. But in proposed DI-AIT will be lowest blocking probability due to Q-learning. Because with time the system will learn enough and now SU will not sense the channel but directly select the channel having highest Q-value. Hence with decrease in packet per second. In the beginning the blocking probability for GAS and DI-

AIT scheme is same but due to Q-learning it will be lowest for proposed scheme DI-AIT to increase the efficiency of SU.

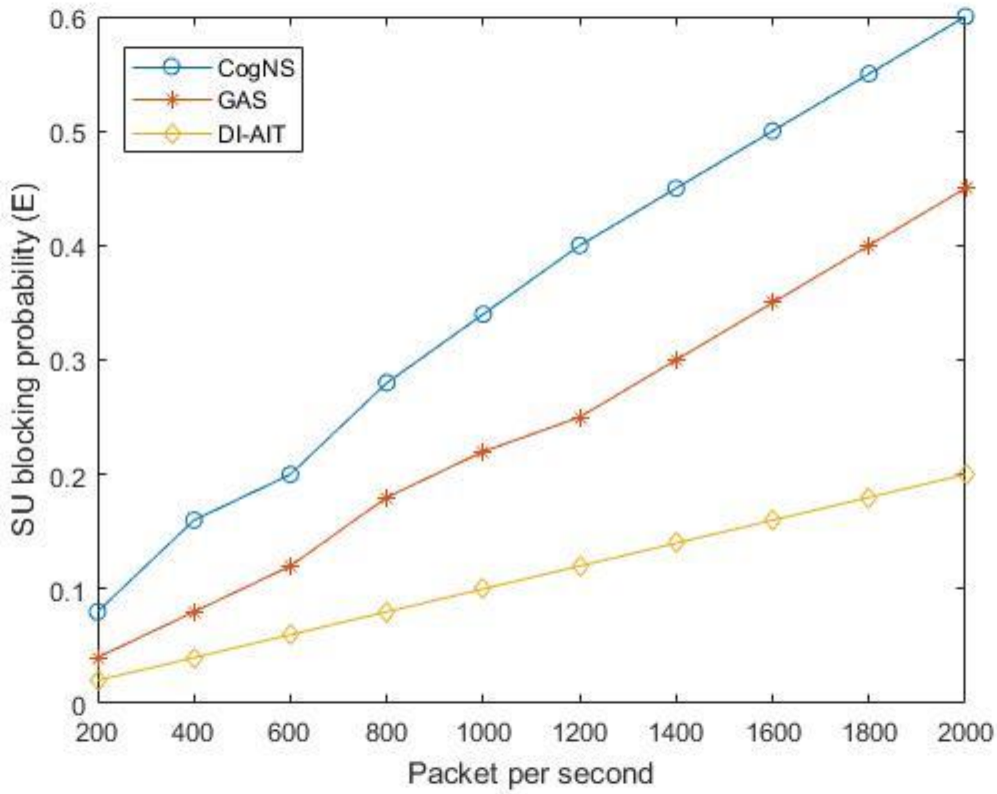

Figure 14: SU Blocking probability vs Packet per second

The SU blocking probability also varies with increase in simulation time. In CogNS scheme the SU blocking probability will be high as simulation time increase the chances of PU to reappears will be high hen blocking probability will also be high. But in GAS scheme as PU and SU communicate concurrently hence its blocking probability will be lower with increase in time than CogNS. But in proposed scheme DI-AIT it will be much less than previous both scheme because of Q-learning. With increase in time the SU has learned much and maintains it Q-table where probability of PU to reappear is much low and SU can now send with high transmission power. Hence its blocking probability will be the lowest. The Q-table is updated according to change in traffic patterns. At start, the blocking probability for GAS and DI-AIT scheme is same but due to Q-learning it will be lowest for proposed scheme DI-AIT to increase the efficiency of SU.

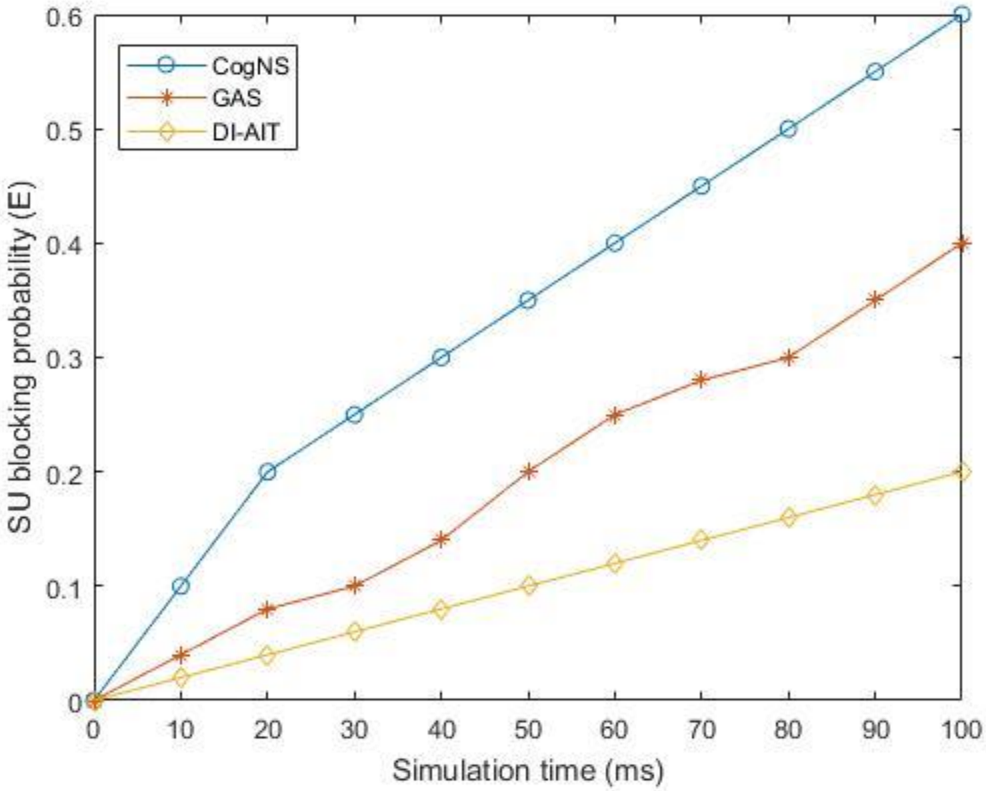

Figure 15 SU Blocking probability vs Simulation time

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Our work presented the Distributed intelligent channel access with adaptive IT (DI-AIT) scheme to solve dynamic channel allocation problem using underlay technique and Q-learning. The changes in the results are due to different traffic patterns which abruptly changes. The proposed DI-AIT scheme is to allocate best available channel to SU to increase the channel QoS such as throughput, delay and energy. And to dynamically optimized the channel interference threshold value which results in increase in higher QoS.

The performance evaluation to proposed DI-AIT scheme is conducted with two other different scenarios using NS-2 and MATLAB. Numerical analysis shows that proposed scheme achieves better performance in comparison of another scheme as well as in terms of energy consumption. The metrics used in this study for the evaluation of the proposed scheme covers all the major aspects of scheme.

5.2 Future work

We will further study about spectrum efficiency of DI-AIT especially for reduction of delays incurred in transmission of packets and energy consumption. Also, the problem is to update the Q-table due to change in traffic patterns which will affect the overall performance of the system.

We will conduct same experiment using different routing schemes and communication standards which should be implemented further to improves the aspects of energy of sensor nodes and end-to-end delay for packet delivery.

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