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Priority Based Dynamic Spectrum Management using Virtual Utility Functions in Cognitive Radio Enabled Internet of Things

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Abstract— **Fast growth of wireless devices in IoT (Internet of Things), industry 5.0 and 6G cellular networks, is dealing with the challenge of spectrum scarcity and uneven utilization of available resources. To achieve Ambient Intelligence (AmI) in IoT communication network, dynamic utilization of available network resources, is a challenge faced by resource constraint IoT devices. Cognitive radio technology enables these devices to intelligently sense the free spectrum hole and smartly manage available channels opportunistically. To jointly deal with the challenge of spectrum scarcity and application specific network service provision, we propose a novel multi-attribute based two-tier framework called Cognitive Radio Efficient Spectrum Utilization (CR-ESU) which integrates the concept of Network Function Virtualization (NFV) as Virtual Utility Functions (VUFs) with cognitive radio enabled IoT devices to achieve the dynamic and flexible network services as well as spectral efficiency. The proposed framework is one of the pioneer works that incorporate the two ground breaking technologies, NFV and CRN to create a smart and flexible CR-enabled IoT network. CR-ESU also ensures the best channel selection using Dynamic Channel Reservation (DCR) scheme to decrease the channel switching rate. Continuous Time Markov Chain (CTMC) model is used for network modeling and mathematical expression formation. Promising results show the potential of CR-ESU framework to form a reconfigurable and efficient network.**

Index Terms—**Cognitive Radio Networks (CRN), Internet of Things (IoT), Ambient Intelligence (AmI), Dynamic Channel Reservation (DCR), Network Function Virtualization (NFV)**

1. INTRODUCTION

CURRENT era of wireless communication, evolving towards industry 5.0 with 6G cellular networks and the internet of things seems to be an evolutionary improvement in networking, providing a diversity of functionalities. Despite all the service provisioning, wireless devices are rapidly increasing hundreds of billions in numbers demanding efficient and reliable network resources, causing the problem of spectrum scarcity [1], [2]. Mobile and IoT devices (sensors, actuators, wearables, and smartphones) growth rate has been increasing by thirty to forty percent every year. The licensed spectrum utilization ranges from 15 to 85% according to a report by the Federal Communication Commission (FCC) [3]. The unlicensed spectrum frequencies are facing heavy congestion while licensed frequencies are not being efficiently utilized in the domain of time and space. That is why the spectrum access technique called Dynamic Spectrum Access (DSA) is the most efficient approach to deal with the challenge of spectrum scarcity [4], [5]. To improve the available spectrum efficiency and achieve DSA, Cognitive Radio Network (CRN) is the best suitable approach, Introduced in 1992, by Joseph Mitola III [6]. The term cognitive in CRs refers to the programmable radios having abilities to manage network parameters autonomously as they are responsible for performing multiple tasks like spectrum sensing, spectrum mobility, spectrum management, and spectrum sharing. In CRN cognitive devices are unlicensed users known as Secondary Users (SUs) opportunistically accessing the free spectrum holes or white spaces of a licensed network, without interfering with the transmission of the licensed user called Primary User (PU). In a CRN architecture, SUs coexist with the licensed wireless network users called primary users without disturbing their transmission as PUs are privileged. CRN operates in three modes, interweave, underlay [7], [8], and overlay [9] to opportunistically access the licensed spectrum.

In an IoT environment, enabling various smart applications does not utilize the spectrum evenly all the time. Some of the allocated portions of the spectrum is over-utilized in one span of time, whereas in the other span of time is underutilized [10]. As IoT devices perform data transmission during different intervals of time as per application requirements, causes non-uniform utilization of the available spectrum. These under-utilized chunks of spectrum are called spectrum holes or white spaces. CR-enabled IoT devices are capable to sense and utilize these spectrum holes for communication unlike other cellular networks and communication protocols like Wi-Fi, Bluetooth, and ZigBee. These wireless technologies are unable to share the spectrum with other devices even if it is under-utilized, which is considered a major drawback of these technologies in an IoT environment. CRN operates on the same 2.4GHz Industrial, Scientific, and Medical (ISM) band which is why it can be combined with other communication protocols to utilize the spectrum efficiently. Enhancement in spectrum utilization efficiency is the key challenge for CRNs, and a major concern of the research community as well. Multiple spectrum allocation techniques are proposed to improve efficiency in

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CRN [11]–[13].

TABLE I
LIST OF ABBREVIATIONS

Abbreviation	Description
3C	Common Control Channel
AmI	Ambient Intelligence
CR-ECM	Cognitive Radio Efficient Channel Management
CR-ESU	Cognitive Radio Efficient Spectrum Utilization
CR-IoT	Cognitive Radio based Internet of Things
CRN	Cognitive Radio Network
CR-VCB	Cognitive Radio VUF Compute Box
CTMC	Continuous Time Markov Chain
DCR	Dynamic Channel Reservation
DSA	Dynamic Spectrum Access
IoT	Internet of Things
IU	Interweave-Underlay
NFV	Network Function Virtualization
PU	Primary User
QoS	Quality of Service
RCL	Reserved Channel List
SDN	Software Defined Networking
SE-CRN	Spectrum Efficient Cognitive Radio Network
SRP	Significant Required Parameters
SU	Secondary User
VCB	Virtual Compute Box
VM	Virtual Machine
VUF	Virtual Utility Functions

In the next section, we will first provide state-of-the-art works proposed in the literature to enhance spectral efficiency, significant contributions of CRs in IoT environments, the background of virtualization techniques in wireless communications, and the research contribution and novelty of our proposed work.

A. Related Work

In recent research efforts, multiple approaches are evaluated and explored to improve dynamic spectrum utilization in cognitive radio networks. Effective spectrum allocation and management is the key to improve network performance and can be achieved through reducing time and cost, minimizing channel switching rate, and improving fairness between SUs [14]. The author in [15], proposed a multichannel assignment algorithm (FMCA) based on MAC protocol to resolve the spectrum sensing and access contention problem. A distributed cognitive radio environment was simulated to resolve the channel assignment problem based on the maximum fairness index of Jain's Fairness criteria. The proposed solution shows significant results to improve fairness between SUs, and increase throughput. The author in [16], merged the NSGA-II algorithm with reinforcement learning and propose an NSGA-RL scheme to deal with the spectrum allocation problem in cognitive radios. The tradeoff between spectral efficiency and network capacity was inspected and manual tuning of parameters was replaced with self-adaption, with the help of a reinforcement reward-based learning technique. Similarly, CR spectral efficiency was improved in [17].

CRNs have to bear interference restrictions while sharing spectrum with PUs, that is why to improve fairness between SUs the auction-based game theory was investigated to deal with the spectrum leasing issues. The author in [18] addressed the adjacent channel interference problem and introduced Guard-Band Aware framework to deal with the channel assignment problem considering the Rayleigh Fading effect. The scheme operated in batch mode, significantly improves the network performance by reducing the number of assigned channels to each user. For delay-sensitive and bandwidth-hungry applications, an online learning-based mechanism was adopted in [19] to meet the QoS demands of the network. The proposed approach was compared with the existing dynamic least interference algorithm, cognitive cross-layer algorithm, and dynamic learning algorithm, to evaluate its performance, and outperformed the aforementioned frameworks. The author proposed an S-D pair-based channel allocation and spectrum utilization scheme as a linear integer optimization problem in [20] whereas the author in [21] utilized a mathematical approach and proposed a fuzzy logic-based decision support system to improve the channel allocation and selection process in cognitive radio networks. The framework jointly used IU mode, considering channel selection parameters and minimized SU handoff rate eventually increasing network throughput. All these approaches have contributed effectively to improve the CRN performance but overlooked the heterogeneous nature of wireless communication. Which requires a smart and dynamic approach to provide application-specific services autonomously, according to transmission requirements.

Cognitive radio-enabled devices can be an optimal solution for the uneven and non-uniform bandwidth requirements of the IoT network environment as well. The legacy wireless technologies do not seem to fulfill the requirements of IoT devices efficiently as these technologies do not have cognitive and sensing abilities to sense external obstacles while connecting far-distance base stations. CRN-enabled IoT environment can seamlessly overcome these limitations apart from maintaining the spectrum utilization efficiency. A proactive asymmetric and asynchronous channel hopping algorithm for CR-based IoT devices was proposed in [10]. The scheme resolved the synchronization of the global clock problem of a heterogeneous environment of SUs by maintaining the minimum rendezvous intervals. The author in [22] used a statistical approach for spectrum assignment in CR-IoT devices and reduced the probability of jamming attacks on the network. So that devices can communicate on the most secure available channels to maintain a certain QoS level. A purchase-based scheme was proposed in [23] to improve spectral efficiency by trading off the spectrum price with access benefits for IoT users. SE-CRN for 5G base IoT devices has been proposed in [24]. The author introduced a novel approach consisting two algorithms i.e. SE-DSA and SE-DCR that jointly worked to achieve dynamic spectrum access. Dynamic channel reservation was employed in SE-DCR to minimize the handoff rate and increase the channel availability while keeping the channel failure rate into consideration.

TABLE II
LIST OF NOTATIONS

Notation	Description
Ch_{idle}^{N}	Total number of free available channels
Ch_{idle}^{T}	Total idle time of a channel
CC_{Req}	Required channel capacity

N_{Ch}	Total number of channels
N_{SU}, N_{PU}	Number of SUs, number of PUs
N_V	Total number of virtual machines
SU_{High}^N	Number of high priority SU in a particular state x
SU_{Low}^N	Number of low priority SU in a particular state x
SU_{RCL}	SU reserved channel list
SU_{RCL}^N	Number of reserved channels in SU_{RCL}
TP_{SU}	SU transmission power
T_{RCL}	Time interval after each RCL is updated
T_{Tr}	Transmission time
VUF_{High}	VUF service for high priority SUs
VUF_{Low}	VUF service for low priority SUs
$\lambda_{hh}, \lambda_{sh}$	Hard handoff rate, soft handoff rate
λ_{PDR}	Packet drop rate
λ_{PTR}	Packet Transfer rate
λ_{PU}	PU arrival rate
λ_{SUH}	SU_{High} arrival rate
λ_{SUL}	SU_{Low} arrival rate
$SINR$	SU Signal-to-interference-plus-noise-ratio

There are no doubts about the potential benefits of the improvements made in the literature to increase spectral efficiency in CRN. But the era of next-generation IoT devices and industry 5.0 demands ambient intelligence-based smart networks to provide application-specific services while avoiding the issue of spectrum scarcity. The Integration of trend-changing virtualization technologies like Network Function Virtualization (NFV) with cognitive radios, is a potential way to gain a certain QoS level of current network requirements, dynamic reconfiguration of utility functions, and cost-effectiveness.

NFV is an emerging virtualization technique that separates network instances from hardware platforms and decouples network functionality from physical location by leveraging faster virtualization techniques [25]. Using software virtualization techniques, network functions can be implemented on commodity hardware like standard servers, switches, and storage. NFV technology instantiates these virtual appliances according to the user's demand without installing any additional hardware. The telecommunication and wireless communication industrial landscape has dramatically changed by the benefits and innovations introduced by the NFV technology which also reduces the operational cost of infrastructure deployment.

There is very little work reported in literature that made efforts in cognitive radio virtualization to aim for flexible network services. The author in [26] proposed a CRVNE (Cognitive Radio Virtual Network Environment) architecture that represents the CR model with two active layers; Primary Virtual Network (PVN) and Secondary Virtual Network (SVN) and maps them in an overlay manner. This mapping ensures less collision probability and fair resource allocation. This mapping lacks the efficient channel selection approach to minimize the number of handoffs. A Genetic Algorithm (GA) based scheme was proposed to achieve better QoS and to minimize the rate of SU blocking and dropping of SU. CRN has great abilities of Autonomous Network Management (ANM) like self-management, self-optimization, cognition, self-X functions, monitoring, and observation. The author in [27] proposed a novel framework of NFV combining SDN in cognitive radio networks using Virtual Utility Functions (VUFs). This is the very first approach that combines ANM, SDN, NFV, and SDR to achieve efficient DSA, reconfiguration flexibility, and network efficiency. The framework was tested on real-time testbeds ORBIT and IRIS, sponsored by ORCA (Orchestration and Reconfiguration Control Architecture) EU project. The framework was successful to achieve reconfiguration flexibility, fair channel allocation, and collision avoidance among cognitive radios but did not consider the best quality of channel for channel selection to decrease channel switching rate, that has a significant impact on network performance. Additionally, the approach used only interweave mode and did not utilize the benefits of hybrid IU mode. Moreover, CR virtualization techniques have never been explored for IoT-based environments which could be a significant contribution.

To fulfill the research gaps in the literature and to explore the benefits of groundbreaking technologies like NFV with intelligent devices like cognitive radios, in this article, we propose a novel multi-attribute based approach CR-ESU for IoT based CRN. The significance and contribution of the proposed work is explained below.

B. *Novelty and Contribution*

Merging CRN with NFV can efficiently resolve spectrum scarcity, providing intelligent, dynamic, and customizable network services, without increasing hardware equipment costs. That is why we aim to utilize the concept of NFV by integrating Virtual Utility Functions (VUFs) [27] through a Virtual Compute Box (VCB) into cognitive radios and propose a novel multi-attribute based two-tier framework called Cognitive Radio Efficient Spectrum Utilization (CR-ESU), to achieve the dynamic and application-specific network services. CR-ESU scheme consists of further two algorithms called Cognitive Radio VUF Compute Box (CR-VCB) and Cognitive Radio Efficient Channel Management (CR-ECM). SUs are able to switch their role as SU_{High}, for bandwidth hungry and delay-sensitive applications, and as SU_{Low}, for non-delay sensitive services. The framework ensures the provision of dynamic and reconfigurable services while maintaining the QoS level of high priority transmissions of SU_{High}. CR-VCB computes the appropriate VUF for requesting SU, whereas CR-ECM manages to dynamically allocate channels to SUs while utilizing the available spectrum efficiently using hybrid IU mode. The contribution and significance of this article are summarized as follows.

- *Comprehensive state-of-the-art literature:* A comprehensive and detailed analysis of literary work and its limitations is provided to explain the reasonable grounds for the proposed work and the need of the hour.
- *A novel framework:* In the light of state-of-the-art and to the best of our knowledge CR-ESU framework is one of the pioneer works that integrate the concept of NFV with cognitive radios to provide dynamic, intelligent, and reconfigurable service roles of SUs while keeping the efficient spectrum allocation into consideration.
- *Performance efficient results:* For result comparison and analysis, in this article, we provide the comparison of the

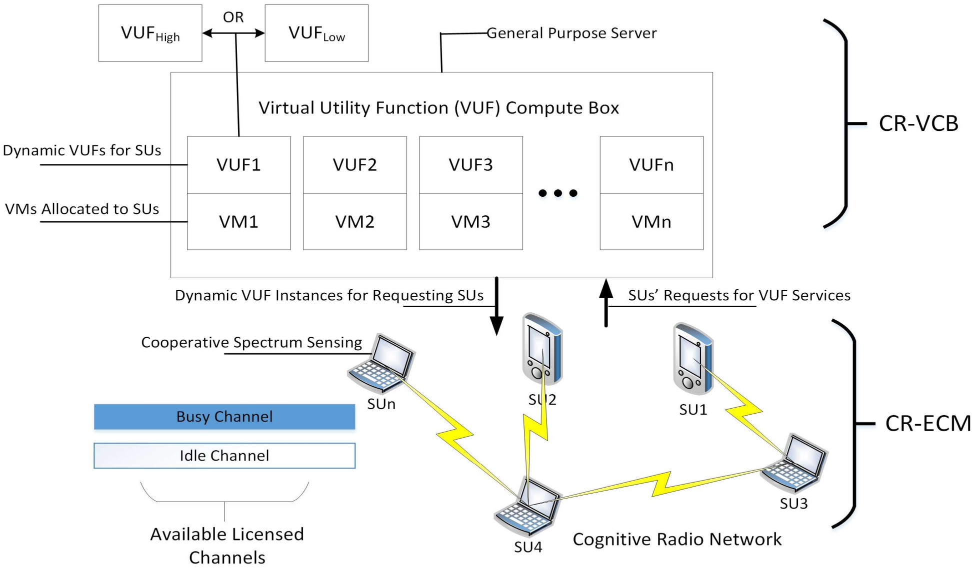


Fig. 1. High level system diagram of proposed framework CR-ESU

proposed scheme with SE-CRN [24]. The comparative results based on significant performance metrics, show that due to the dynamic and flexible framework, and efficient channel selection scheme, CR-ESU outperformed the SE-CRN framework.

C. Paper Organization

The remaining section of the article is organized as follows. Section II elaborates the proposed framework CR-ESU, working of its components CR-VCB and CR-ECM, the system model, and its performance evaluation parameters. Simulation settings and comparative results are discussed and evaluated in section III. The complete contribution and significance of the work are concluded in section IV.

2. PROPOSED FRAMEWORK

The proposed framework CR-ESU as shown in Fig. 1, consists of two major schemes called CR-VCB and CR-ECM. Both schemes jointly work to achieve dynamic, priority-based reconfigurable services and efficient spectrum utilization within SUs, keeping their transmission transparent to PUs. The following section explains the working of each scheme in detail.

A. Cognitive Radio VUF Compute Box (CR-VCB)

CR-VCB is responsible to dynamically compute appropriate VUF for requesting SU as per provided SRPs. SRPs are the significant required parameters that determine the data transmission requirements for a specific application, either to be delay-sensitive or not. The respective VM utilizes received SRPs as the input parameters of fuzzy logic-based decision controller to decide the suitable VUF to be configured on requesting SU for the specific transmission requirements as shown in Fig. 2. TP_{SU}, $SINR$ and CC_{Req} are the selected SRPs used as input parameters for fuzzy logic-based decision controller ranging as high, medium, and low. High to medium range of TP_{SU}, $SINR$ and CC_{Req} indicates the delay-sensitive transmission requirements and results as VUF_{High} for the respective SU called SU_{High}. TP_{SU}, $SINR$ and CC_{Req}, ranging from medium to low indicates the low priority and delay insensitive data transmission requirements, resulting as VUF_{Low} for the respective SU called SU_{Low}. The inference rules given to the fuzzy logic controller are followed as described in [21] and surface results are shown in fig. 4. The selected service request parameter CC_{Req} is the channel capacity required for the particular data transmission, while TP_{SU} and $SINR$ are defined as follows:

- *SU Transmission Power* TP_{SU} - is the power at which SU transmits its data without risking the harmful interference level of PU and neighboring SUs as well. SU can transmit its data using its full initial power in interweave mode but have to minimize and adjust its level to a given threshold and has to switch to underlay mode, in case any PU activity is detected nearby, to avoid harmful interference. Using the Common Control Channel (3C) available in open loop path loss is estimated and thus the initial value of TP_{SU} is calculated as follows:

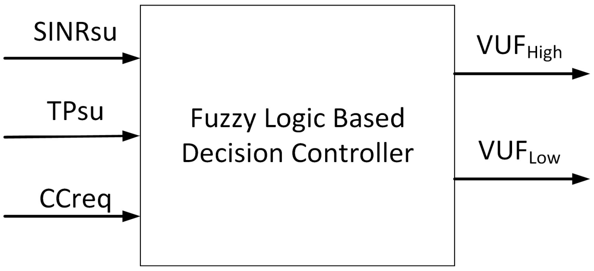


Fig. 2. Fuzzy Logic-based decision controller taking SRPs as input

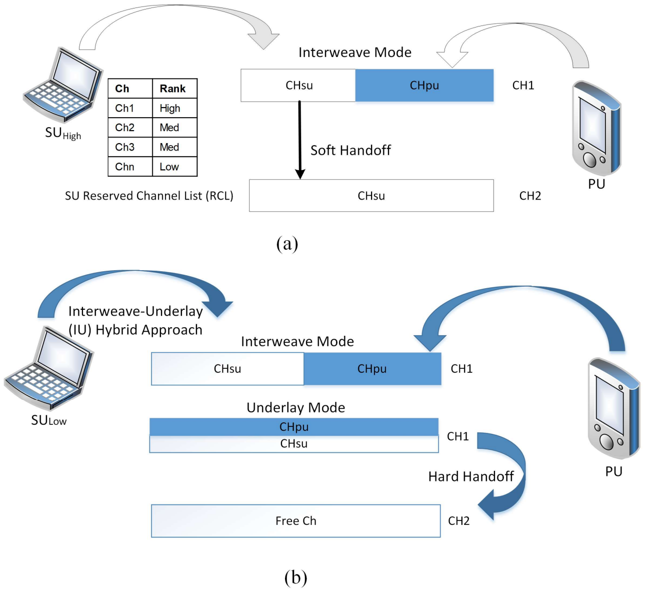


Fig. 3. (a) High priority SU RCL and Interweave approach, (b) Low Priority SU and hybrid IU approach

$$TP_{SU} = TP_{3C} - TP_{3C}^{Rx} - f_{glt} + X_{SU} + \sum_{i} l_i + SINR_{Req} \qquad (1)$$

Where TP_{3C} is the determined value of power at 3C and its calculated power at the SU receiver side is denoted with TP_{3C}^{Rx}.

The value of gain, loss, and tolerance is represented by f_{glt}. The final calculated value of the signal-to-interference-plus-noise-ratio is denoted by $X_{SU} + \sum_i l_i$. Whereas, $SINR_{Req}$ is the required SINR for SU to transmit its data. For opening communication, SU transmitter and receiver uses the initially calculated value of TP_{SU}, with time it can be tuned and updated according to the given threshold to avoid harmful interference for PU and other SUs operating on the same channels.

- $SINR$ - The parameter plays an important role to ensure a certain level of QoS in SU transmission is signal-to-interference-plus-noise-ratio. $SINR$ calculated on SU receiving antenna is used to determine the minimum value of SU transmission power, required to maintain a specific level of quality of transmission [28]. This minimum value of TP_{SU} can be calculated as
$$TP_{SU_{min}} = SINR_{Rec} - SINR_{Cal} \qquad (2)$$
The value of $SINR_{Cal}$ on receiving antenna can be calculated as [1].

$$SINR_{Cal} = \frac{TP_{SU\_B}.\,|P_{22}|_B^2}{\sum_{\substack{i=1\\ i\neq X}}^{L} |P_{22}|_i^2.\,TP_{SU\_i} + \sum_{j=1}^{M} |P_{12}|_j^2.\,TP_{SU\_j} + \Omega_{SU\_X}^2} \qquad (3)$$

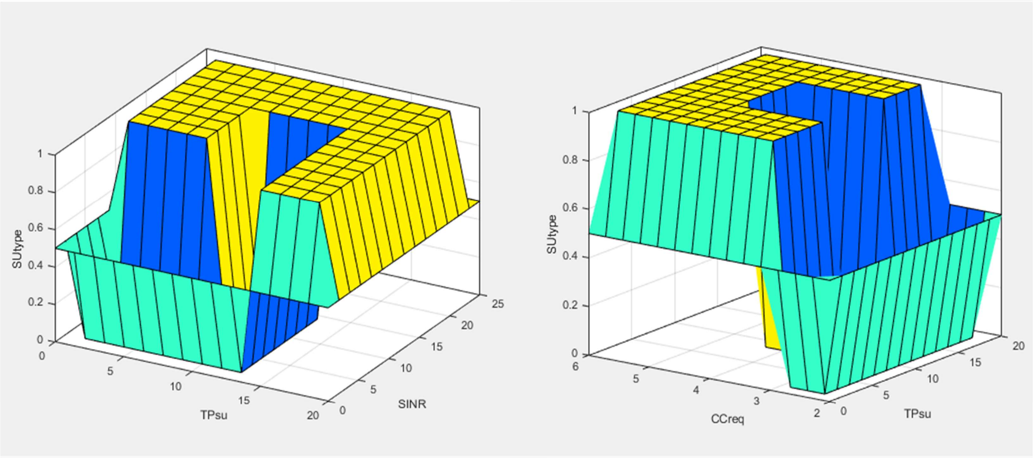
Where, L and M denote the number of co-channel PUs and SUs. $|P_{ij}|^2$ is the power gain of fading channel coefficients. The transmitted power of neighbor SUs operating on the same channels are represented by TP_{SU_X}, TP_{SU_i}, and TP_{SU_j}, while $\Omega_{SU\_X}^2$ represents the variance of additive white Gaussian noise at SUs.

B. Cognitive Radio Efficient Channel Management (CR-ECM)

CR-ECM framework ensures efficient channel allocation and management within SUs. To guarantee dynamic and seamless transmission services with a minimum number of spectrum handoffs. Our framework categorizes the SUs roles as SU_{High} and SU_{Low}. These roles can dynamically be reconfigured every time SU makes a service request to its respective virtual machine according to its transmission requirements. SU_{High} transmits delay-sensitive data that is why operate on interweave mode and reserve SU_{RCL}^{N} number of free available channels reserved in its SU_{RCL}, that dynamically gets updated after an interval of time T_{RCL}. SU_{High} determine the maximum value of SU_{RCL}^{N} as

$$SU_{RCL}^{N} = {}^{1}\!/_{2}\ Ch_{idle}^{N} \qquad (4)$$

where; $SU_{RCL}^{N} \geq 0$ and Ch_{idle}^{N} is the number of idle channels in the network.



(a) (b)

Fig. 4. VCB Fuzzy Logic Controller surface results taking TP_{SU}, $SINR$ and CC_{Req} to decide SU priority

TABLE III
CTMC STATE TRANSITION TABLE

	Current activity	Destination state and condition	Transition rate
1.	SU_{High} arrives, free channels are available	$(SU_{High}^{N}+1, SU_{Low}^{N}, N_{PU}, N_{Ch}, SU_{RCL}^{N}, L_{SU})$	λ_{SUH}
2.	PU arrives on the channel SU_{High} is operating.	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}+1, N_{Ch}, SU_{RCL}^{N}, L_{SU})$	λ_{PU}
3.	SU_{High} makes soft handoff to channel in RCL	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}, N_{Ch}, SU_{RCL}^{N}-1, L_{SU}), SU_{RCL}^{N} > 0$	λ_{SUH}
4.	PU arrives on the channel SU_{High} is operating.	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}+1, N_{Ch}, SU_{RCL}^{N}, L_{SU})$	λ_{PU}
5.	No channel is available in RCL, SU_{High} terminates and wait for scanning	$(SU_{High}^{N}-1, SU_{Low}^{N}, N_{PU}, N_{Ch}, SU_{RCL}^{N}, L_{SU}), SU_{RCL}^{N} = 0$	λ_{SUH}
6.	SU_{Low} arrives, free channels are available	$(SU_{High}^{N}, SU_{Low}^{N}+1, N_{PU}, N_{Ch}, SU_{RCL}^{N}, L_{SU})$	λ_{SUL}
7.	SU_{Low} operates on interweave mode	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}, N_{Ch}, SU_{RCL}^{N}, L_{SU}-1), L_{SU} > 0$	λ_{SUL}
8.	PU arrives on the channel SU_{Low} is operating	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}+1, N_{Ch}, SU_{RCL}^{N}, L_{SU})$	λ_{PU}
9.	SU_{Low} operates on underlay mode on same channel	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}, N_{Ch}, SU_{RCL}^{N}, L_{SU})$	λ_{SUL}
10.	PU arrives on the channel SU_{Low} is operating.	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}+1, N_{Ch}, SU_{RCL}^{N}, L_{SU})$	λ_{PU}
11.	SU_{Low} switch to new channel	$(SU_{High}^{N}, SU_{Low}^{N}, N_{PU}, N_{Ch}, SU_{RCL}^{N}, L_{SU}-1), L_{SU} > 0$	λ_{SUL}
12.	No free channel available, SU_{Low} terminates and wait for scanning	$(SU_{High}^{N}, SU_{Low}^{N}-1, N_{PU}, N_{Ch}, SU_{RCL}^{N}, L_{SU}-1), L_{SU} = 0$	λ_{SUL}

To ensure the level of QoS it is very critical and challenging to decrease the number of hard handoffs during SU transmission because of PU arrival on the same channel. To minimize the hard handoff rate λ_{hh}, proposed algorithm for SU_{High} places the reserved channels in SU_{RCL} according to their ranks denoted as Ch_{Rnk}. Considering the heterogeneous nature of the environment, channels with different qualities and different attributes are labeled as different ranks indexing in SU_{RCL} in descending order as sown in Fig. 3. The rank of a particular available channel is calculated as

$$Ch_{Rnk} = \frac{Ch_{idle}^{T}}{(Ch_{busy}^{T} \times No\ of\ PU\ Arrivals_{Ch}^{T}) + Ch_{idle}^{T}} \quad (5)$$

Where Ch_{idle}^{T} is the total idle time of a particular channel and Ch_{busy}^{T} is the total busy time measured over channel Ch in time T. While the number of PU arrivals sensed on a channel Ch on a unit time T is denoted as $No\ of\ PU\ Arrivals_{Ch}^{T}$. In case of any PU activity detected during SU_{High} ongoing transmission, instead of scanning for new free available channel and making a hard handoff, SU_{High} immediately make a soft handoff to an already reserved channel whose rank is indexed as high and update the value of Ch_{RCL}. This kind of soft handoff or channel switching ensures the continuity and quality of delay-sensitive transmission and minimizes the transmission delay.

We assume that SU_{Low} transmission is non delay sensitive and can be continued in underlay mode as well. The proposed algorithm for SU_{Low} operates on hybrid IU mode to ensure seamless transmission of low priority SUs as well. SU_{Low} can transmit in its full power in interweave mode on channels that are freely available and are not in SU_{High} reserved channel list. In case any PU activity is detected, SU_{Low} switch to underlay mode and minimize its transmission power TP_{SU} to a defined threshold. That is how, SU_{Low} can continue its transmission without causing any harmful interference to PU, as shown in Fig. 4. In case SU_{Low} cannot maintain its transmission even in underlay mode, It can handoff to free available non-reserved channel. This IU hybrid approach significantly reduces the channel switching rate and eventually increases the network throughput.

C. *System Model and Assumptions*

We assume a distributed cognitive radio network environment with N_{SU} number of mobile SUs and a primary network environment with N_{PU} number of PUs. The primary network consists of N_{Ch} number of total channels available for transmissions bearing variable capacities where N_{Ch} is a positive integer. N_{V} is the number of virtual machines created on a general-purpose server located in the user premises within the cognitive radio network, where N_{V} is equal to N_{SU}. The cooperative spectrum sensing technique [27] has been used for PU arrival and free channel availability sensing. A VM is allocated to each SU to compute the requested service for the respective VUF. Requested VUFs can be instantiated or configured on respective SU as per given Service Request Parameters (SRPs). A common and dedicated control channel is used for local and global control messages within the network. SU sends SRPs to its respective VM located in CR-VCB, which computes appropriate VUF service accordingly, using Fuzzy Logic based decision controller [21] and instantiate the reconfigurable service on requesting SU. SU_{High} transmit on interweave mode, dynamically maintain Reserved Channel List (RCL), updated within every interval of time T_{RCL}, to reduce the number of hard handoffs. While SU_{Low} transmits delay insensitive data that is why does not reserve channels but operate on interweave mode and switch to underlay mode in case of PU arrival, while maintaining its transmission power TP_{SU} to a specific threshold. PU arrival during SU transmission and SU service requests for VUFs observe poison distribution with the rate of δ_{P} and δ_{S}. Service time of SUs is assumed to follow exponential distribution. We assume non-overlapping N_{Ch} number of data channels modeled as Idle and Busy state following Markov 2-State model. We assume that SUs perform perfect spectrum sensing and sensing delay is considered negligible [24] in order to evaluate the performance of proposed framework particularly on specific parameters.

D. *Continuous Time Markov Chain Modeling*

In order to model the proposed framework according to Continous Time Markov Chain Model (CTMC) let S be the set of all possible states of CR-ECM and are denoted by x, where

$x = (SU^N_{High}, SU^N_{Low}, N_{PU}, N_{Ch}, SU^N_{RCL}, L_{SU})$. Here SU^N_{High}, SU^N_{Low}, N_{PU}, and N_{Ch} is referring to the number of SU_{High}, number of SU_{Low}, the number of PUs and the number of channels in the network. SU^N_{RCL} and L_{SU} are the number of reserved channels in SU's RCL and the number of free channels that are not in SU's RCL. $\beta(x)$ represents the sum of all busy channels in the entire CRN. Idle channels for SU_{High} in a particular state x can be derived as $H_{SU}(x) = N_{Ch} - \beta(x)$, while free channels for SU_{Low} in a particular state x are $L_{SU}(x) = N_{Ch} - (\beta(x) - \omega(x))$, where $\omega(x)$ is the number of channels reserved by neighbor SU_{High} under state x. The initial state of state transition table is given as $x = (SU^N_{High}, SU^N_{Low}, N_{PU}, N_{Ch}, SU^N_{RCL}, L_{SU})$, the list of all possible states of CTMC with state conditions and next state transitions is presented in Table III. We denote the steady-state probability of state x with $\mu(x)$, and can be measured in a particular state, as

$$\mu B = O, \sum_{x\epsilon S} \mu(x) = 1 \tag{6}$$

Where B is the transaction rate matrix derived from Table III, steady-state probability vector is denoted with μ and O is the vector having one row and zero entries.

To evaluate the efficiency of the proposed framework, we study three QoS parameters,

1. *Hard handoff rate* λ_{hh} - To ensure seamless transmission, this is very crucial to reduce the number of hard handoffs within the spectrum, which cause packet loss and transmission delay. λ_{hh} can be defined as the number of hard handoffs SU makes within a particular transmission time T_{Tr}, where $\lambda_{hh}(x)$ is the hard handoff rate of SUs in a state x and $x\epsilon S$.
2. *Throughput* – is defined as the total number of packet transferred from source to destination node, within a specific amount of time t. Throughput can be calculated as
$$Throughput = (\lambda_{PTR} \times T_{Tr}) - \lambda_{PDR} \tag{7}$$
Where, λ_{PTR} is the packet transfer rate and λ_{PDR} represents the packet drop rate due to hard handoff or channel failure.
3. *Service response delay* T_{SRD} – is defined as the total time VCB takes to fulfill service requests SUs in a particular span of time t. T_{SRD} can be calculated as
$$T_{SRD} = \sum_{SU_{High}, SU_{Low}}^{n} SU^N_{SR} \Big/ t(x) \times T_{SRT}, x\epsilon S \tag{8}$$
Where, $\sum^n_{SU_{High}, SU_{Low}} SU^N_{SR}$ is the sum of the total number of service requests made by SU_{High} and SU_{Low} within specific time t, and T_{SRT} is the amount of time VCB takes to fulfil one service request.
4. *Transmission delay* – Is defined as the delay that happens to complete the data transmission from source SU to destination SU within a particular transmission time T_{Tr}. Transmission delay can be calculated as
$$Transmission\ delay = T_{SRD} + {}^{D}\!/_{T_{Tr}(x)}, x\epsilon S \tag{9}$$
5. *Channel availability* – for SU_{High} and SU_{Low} can be formulated as

$$SU^{ChA}_{High} = 1 - \sum_{H_{SU}(x)} \mu(x) \tag{10}$$

$$SU^{ChA}_{Low} = 1 - \sum_{L_{SU}(x)} \mu(x) \tag{11}$$

TABLE IV

LIST OF SIMULATION PARAMETERS AND THEIR RESPECTIVE VALUES

Parameters	Settings
Simulation time	50-200 sec
Simulation area	1000×1000 m
Mobility model	Random Waypoint
λ_{PU}	2-16 per unit time
λ_{SU}	4-16 per unit time
Transmission power in interweave mode	5 W
Transmission power in underlay mode	0.05 W
Time to sense new channels for hard handoff	1 sec
PU detection time	1 ms
Threshold value	1.16 dB
Channel capacity	2-6 $Mbps$
Service response time	0.5 sec
SU waiting time for scanning	3 sec

3. RESULT AND DISCUSSIONS

This section presents the numerical representation of the results of our proposed scheme on the selected QoS evaluation parameters, hard handoff rate λ_{hh}, throughput, transmission delay, service response delay T_{SRD} and channel availability. The VUF computation and configuration, of each time SU makes a new service request, may cause a minor delay but the proposed scheme works in a distributed manner and enables SU to dynamically switch its role according to transmission requirements. It empowers SUs, to select the best available channel and utilize the available spectrum in a distributed manner without any central entity involved. This approach balances the amount of delay caused by VUF computation dynamically and also outperforms SE-CRN [24], which causes more control overhead due to its centralized nature. In traditional virtualization approaches the VMs are typically located on remote cloud server causing more transmission delay while CR-ESU utilizes the general-purpose server within user premises and create dedicated VM for each SU, reduces the computation load and delay. As N_{SU} is equal to N_V that is why the increase in the number of dedicated VM may cause the computation load over the server depends upon server specifications.

To compute and evaluate the performance of the proposed framework, we have simulated the system model and CR-ESU using MATLAB with the simulation settings and parameters given in table IV. In order to ensure fairness in comparative results SE-CRN is deployed with same simulation settings as proposed scheme.

The following section shows the comparative results and analyze the effect of increasing transmission time T_{Tr}, PU arrival rate λ_{PU}, and SU arrival rate λ_{SU} on performance evaluation parameters mentioned in section II (D).

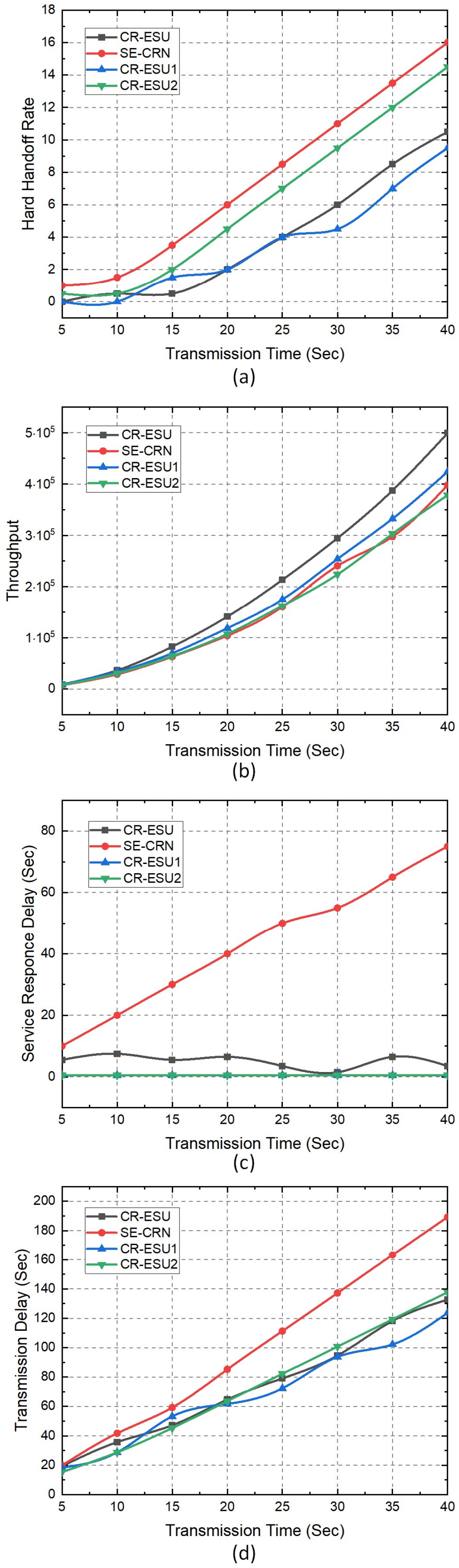


Fig. 5. Comparative results of proposed scheme CR-ESU with SE-CRN, CR-ESU1 and CR-ESU2, analyzing the effect of transmission time T_{tr} on (a) hard handoff rate λ_{hh}, (b) throughput, (c) service response delay T_{SRD}, and (d) transmission delay

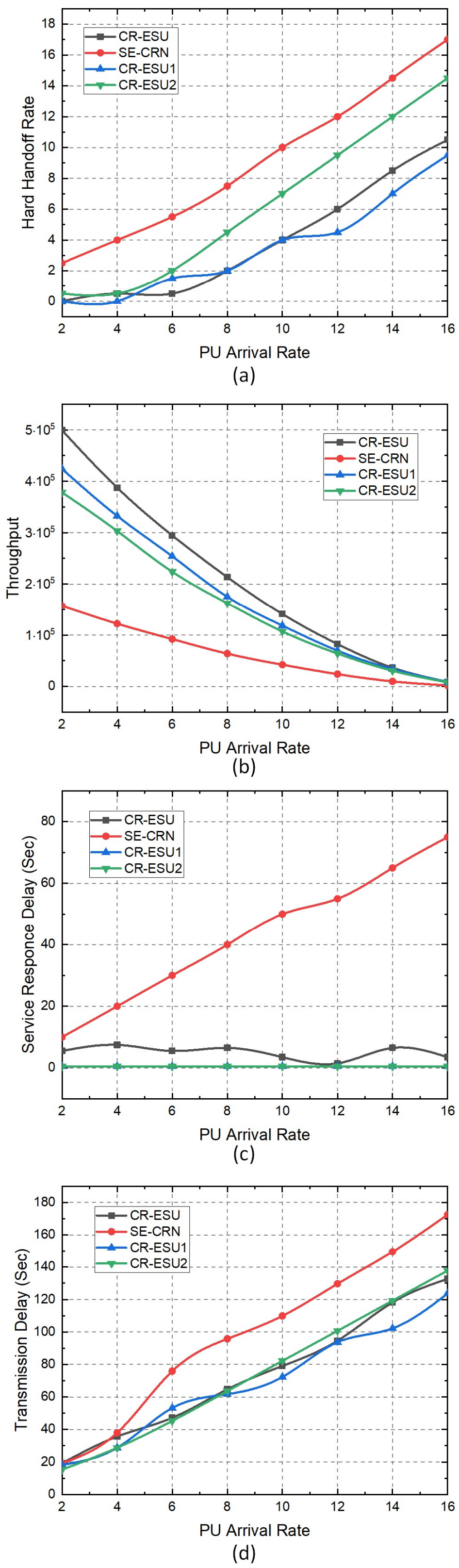
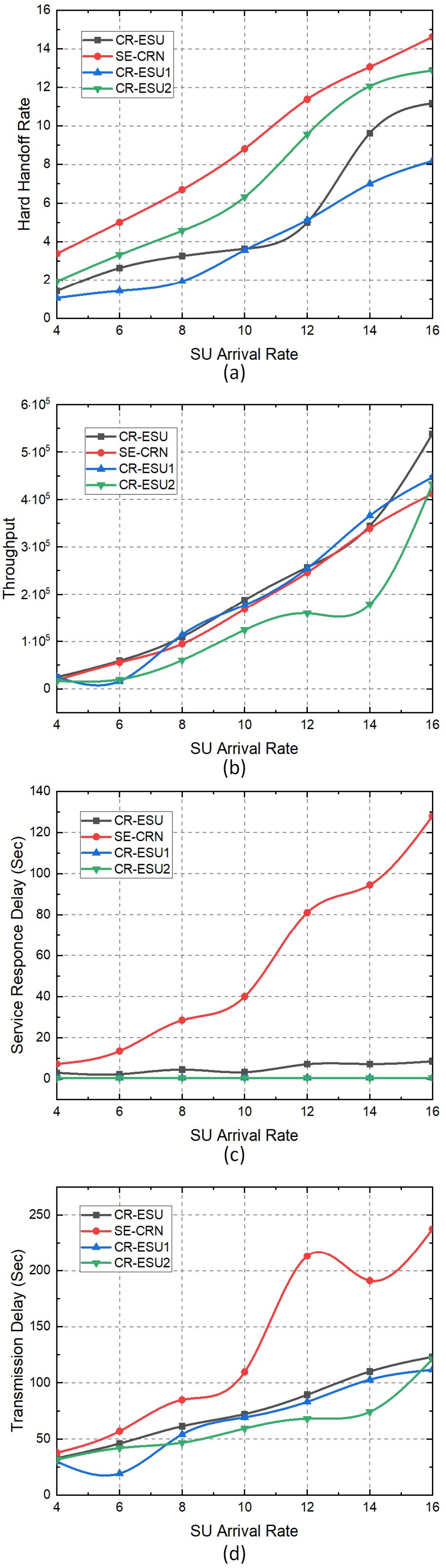


Fig. 6. Comparative results of proposed scheme CR-ESU with SE-CRN, CR-ESU1 and CR-ESU2, analyzing the effect of PU arrival rate λ_{PU} on (a) hard handoff rate λ_{hh}, (b) throughput, (c) service response delay T_{SRD}, and (d) transmission delay



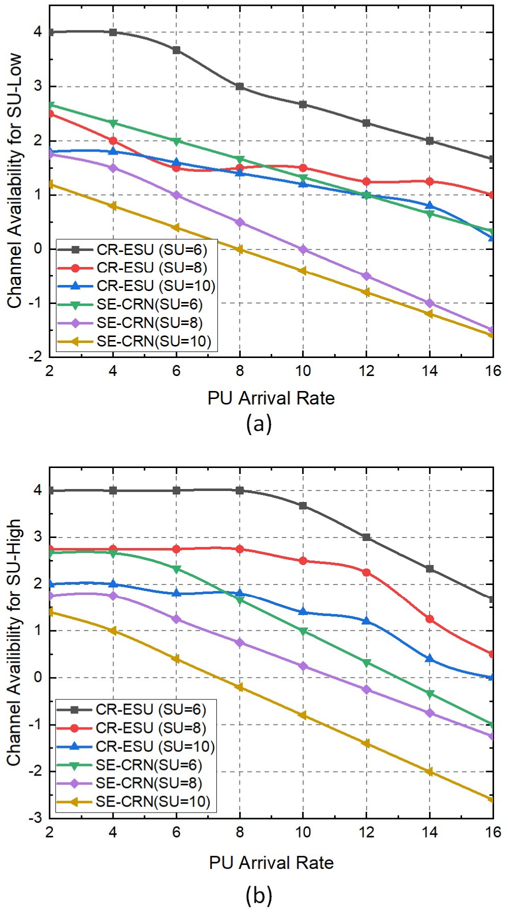
(a)

(b)

(c)

(d)

Fig. 7. Comparative results of proposed scheme CR-ESU with SE-CRN, CR-ESU1 and CR-ESU2, analyzing the effect of SU arrival rate λ_{SU} on (a) hard handoff rate λ_{hh}, (b) throughput, (c) service response delay T_{SRD}, and (d) transmission delay



(a)

(b)

Fig. 8. Comparative results of proposed scheme CR-ESU with SE-CRN, analyzing the effect of PU arrival rate λ_{PU} on (a) channel availability for SU_{Low}, SU_{Low}^{ChA} and (b) channel availability for SU_{Hig} , SU_{High}^{ChA} where $\lambda_{SU} = \{6, 8, 10\}$

A. *Increasing Transmission Time* T_{Tr}

Fig. 5. represents the comparative results of proposed scheme CR-ESU with SE-CRN. To evaluate the network performance of high priority nodes SU_{High} and low priority nodes SU_{Low} separately, CR-ESU1(representing SUs_{High}) and CR-ESU2 (representing SUs_{Low}) are plotted separately as well, with the function of T_{Tr}. The value of T_{Tr} ranges from 5 to 40 sec whereas $\lambda_{SU} = 10$, and $N_{Ch} = 15$. Fig 5(a). shows there is a visible decrease in hard handoff rate λ_{hh} in proposed network due to selection of high ranked channel from RCL for high priority SUs which is lacking in the comparative scheme SE-CRN. The decrease in the value of λ_{hh} is directly proportional to the packet drop rate λ_{PDR} and inversely proportional to the throughput of the network as shown in fig 5(b). Sequentially, fig 5(c), and (d) represent the T_{SRD} and transmission delay respectively. Due to the dynamic switching of SUs in SU_{High} and SU_{Low}, the system shows the fluctuating graph of T_{SRD}. The value of T_{SRD} shows increment only when a SU_{High} request to switch to SU_{Low} or vice versa. Transmission time or λ_{hh} does not affect the service response delay. Unlikely, the comparative scheme CR-ESU bears static numbers of SU_{High} and SU_{Low},

showing increase in T_{SRD} due to its centralized nature. The increment in control overhead is also one of the major causes of high transmission delay. CR-ESU1 and CR-ESU2 represents the transmission of SU_{High} and SU_{Low} respectively with no switching that is why T_{SRD} is static with the value of 0.5 sec. CR-ESU1 reserves channels in RCL and select the best ranked channel available, that is why shows promising decrease in λ_{hh}, and transmission delay, consequently increasing the network throughput.

B. *Increasing PU arrival rate λ_{PU}*

Fig. 6. represents the comparative results of proposed scheme CR-ESU with SE-CRN, CR-ESU1 and CR-ESU2 with the function of λ_{PU} where λ, ranging from (2-16) is poison distribution rate of PU arrival on a channel within time t, $\lambda_{SU} = 10$, and $N_{Ch} = 15$. The increase in λ_{PU} causes increase in hard handoff rate as well as transmission delay, eventually decreasing network throughput. The results clearly show the proposed scheme managed to reduce the hard handoff rate and transmission delay despite of increase in λ_{PU}. Due to dedicated VMs for each SU, increase in λ_{PU} did not affect the T_{SRD} of proposed scheme CR-ESU as shown in fig. 6(c). On the other hand, in SE-CRN central node allocates channels every time a hard handoff occurs, causing huge increment in T_{SRD}. Proposed scheme makes sure that every SU_{High} selects the best ranked channel from RCL with minimum PU arrival probability. Which causes significant decrease in λ_{hh} and increase in throughput. SU_{Low} utilizes the IU hybrid mode of channel management and is able to transmit delay insensitive data in an efficient manner.

– *Channel Availability*

Fig. 8. represents the Comparative results of proposed scheme CR-ESU with SE-CRN, analyzing the effect of PU arrival rate λ_{PU} on (a) channel availability for SU_{Low}, SU_{Low}^{ChA} and (b) channel availability for $SU_{High}, SU_{High}^{ChA}$. Where $\lambda_{SU} = \{6, 8, 10\}$, λ_{PU} ranges from 2-16 and $N_{Ch} = 15$. Due to the dynamic, efficient, and application specific transmission approach, the proposed scheme manages to make more channels available for delay sensitive transmission of SU_{High}. Whereas, hybrid IU mode of channel management resourcefully utilizes the available free channels for non-delay sensitive transmission of SU_{Low} as well. The comparative scheme SE-CRN also reserves channels for high priority SUs but the algorithm does not ensure the best channel selection, causing more channel switching and eventually decrease the channel availability rate for other SUs as shown in fig. 8(b).

C. *Increasing SU arrival rate λ_{SU}*

Fig. 7. shows the variation in results by increasing λ_{SU} and proves the effectiveness of the proposed scheme in the context of network scalability eventually increasing the network throughput. The value of λ_{SU} ranges from 4-16, and N_{ch} =15. CR-ESU scheme supports network scalability without adding any hardware cost due to its VUF based reconfigurable network framework. The result explains that increase in number of SUs, slightly increase the probability of switching service request from SU_{High} to SU_{Low} and vice versa but do not effect very much on the system load causing slight increment in T_{SRD}. On the other hand SE-CRN shows massive increase in T_{SRD} and transmission delay because increase in SUs increase the load on central entity as shown in fig. 7(c). Additionally, scalability causes less channel availability and is directly proportional to λ_{hh} and transmission delay. As, the proposed scheme's algorithm efficiently manages the available channels according to transmission requirements, that is why the fig 7. proves that CR-ESU deals with the scalability issues in a sustainable manner.

4. CONCLUSION

To provide application specific and multi attribute based channel selection and management in IoT enabled CRN environment, we integrated the NFV technology with cognitive radios and proposed a hybrid IU mode based approach called CR-ESU. The proposed scheme enables cognitive devices to switch their roles as SU_{High}, and SU_{Low} for high priority and low priority transmission requirements, consecutively. This dynamic switching according to transmission requirements solve the problem of spectrum scarcity and increase the spectrum utilization efficiency in resource constraint IoT devices. CR-ESU framework consists of two main parts called CR-VCB and CR-ECM work jointly in order to provide seamless and efficient utilization of available spectrum resources while meeting the QoS expectations. CR-VCB consists of dedicated VMs for each SU to provide speedy computation and configuration of required VUF against their service request parameters using fuzzy logic based decision controller. On the other hand, CR-ECM ensures the best channel selection for bandwidth hungry SUs by using dynamic channel reservation algorithm and maintain the channel ranks jointly while providing continuous transmission service to non-delay sensitive SUs, using the hybrid IU mode. We have compared the results of proposed scheme with Spectrum Efficient Cognitive Radio Network (SE-CRN). The comparative results show reduced SRD and control overhead due to the dynamic and distributed nature of proposed scheme. Channel rank selection in RCL ensures the best channel selection for SU_{High}, reducing the hard handoff rate λ_{hh} as compared to SE-CRN. The integration of game changing technologies like NFV and SDN with CRN has s great potential to change the dynamics of future of smart and sustainable networks. In future we aim model our scheme with IEEE 802.22 WRAN standards also adding the factor of channel failure and evaluate the results on bases of some other QoS parameters as well.

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