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# SDN-enabled Cognitive Radio Network Architecture

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**Abstract:** In this study, a new network architecture based on the software-defined networking (SDN) approach is proposed for cognitive radio networks (CRNs). The proposed network architecture [software-defined cognitive radio (SDCR)] assumes the responsibilities of network resource management for CRNs and provides a dynamic spectrum management mechanism with an SDN controller. In this way, the dependency of network users on base stations is reduced in dynamic cognitive radio environments, and network performance is improved by delegating some of the management responsibilities to the controller. The performance analysis of the SDCR is carried out through the RIVERBED MODELER simulation software. End-to-end delays and packet loss rates for the primary network are investigated by selecting different offered loads for secondary users. In addition, for the equal and different packet sizes, primary network and SDCR throughput are examined and network performance is improved by using channel bonding technique. The results indicate that the SDCR outperforms the traditional CRN architecture, in terms of the throughput, and the proposed architecture can provide effective performance. Bit error rate parameter is investigated in the study and the energy consumption parameter of the SDCR is also compared with the cognitive radio wireless network.

## 1 Introduction

Wireless communications technologies have been speedily evolving in recent times. Wireless cognitive radio network (CRN) is one of the outcomes of this development. CRN is a current approach that permits unlicensed users to access the licensed spectrum without interfering with the communication of licensed users. This approach proposes solutions to current problems such as spectrum inefficiency and ineffective use of spectrum for communication technologies.

With these rapid developments, emerging new wireless communication technologies need different requirements. Besides, traditional CRN architecture cannot meet the quality of service (QoS) requirements, and its management is very difficult and complex [1, 2]. Traditional network architecture consists of many routers, switches, and several middle boxes and various complex protocols defined for these network devices [3]. Each new protocol, while solving a number of problems, leads to the construction of more complicated network infrastructure that is more difficult to manage. In addition, non-standard network devices, operating systems, and network control software produced by different vendors are used to manage the network and make various applications on the network. Each network device that is subsequently added to the system increases the complexity and management processes of the networks. Non-standard intermediate network devices from different manufacturers cause security vulnerabilities. Therefore, software-defined networking (SDN) paradigm has been introduced to overcome the aforementioned network problems.

The SDN is a new network approach and it suggests that the integrated data and control planes be abstracted from each other to remove the limitations of the traditional CRN architecture. The SDN offers many possibilities, such as simplifying network and management functions, providing policy-based architecture, applying to existing network infrastructure, and accomplishing autonomous structure. Many different studies about SDN are still in progress in terms of architecture, such as data centres, cloud computing, wireless sensor network technologies. In this study, a new network architecture based on the SDN is suggested to solve the existing CRN architecture problems of wireless CRN technologies. Some management functions of CRN base stations are transferred to the SDN controller to develop a semi-distributed control mechanism. These management functions are dynamic spectrum management, channel bonding technique, service to the maximum number of secondary users (SUs), and scalability of the network. The presence of these functions at the base station makes additional overheads with existing tasks. So, the dependency on the base station is increased. Consequently, these tasks are transferred to a software application on the controller with the SDN approach in this study.

Through this study, while resource virtualisation is performed on the CRNs, dynamic, infrastructure-independent, and efficient resource allocation is provided for SUs (unlicensed). Therefore, while network performance is improved by reducing the overhead of base stations, the dependence of SUs on base stations and physical network resources is also reduced.

The increase in the number of wireless devices also causes an increase in the traffic load. In this context, CRN is one of the important technologies to overcome the spectrum overcrowding encountered in wireless (IEEE 802.11) communication. However, it is seen that traditional CRN architecture suffers from similar problems with today's wireless communication. It is clear that traditional CRN architecture is not suitable for increased management complexity and extremely dynamic wireless network topologies.

In traditional CRN architecture, uncoordinated spectrum access causes interference and low spectral efficiency among SUs. In this study, the SDN approach is used as a solution to these problems encountered in traditional CRN architecture. Through the controller, which is the control plane element developed with the SDN, a coordination that takes control over the spectrum assignment is achieved, and the status of the radio and networks is synchronised.

New algorithms with collaborative approaches are frequently proposed for sensing, multipath fading, shadowing, and receiver uncertainty problems. However, distributed collaborative approaches create negative effects such as extra-sensing time, energy consumption, and delay. In this context, a central


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collaborative approach with the controller, which we consider as a coordination point for the solution of these problems, is proposed.

The rest of this paper is organised as follows. Some related works about CRN and SDN are reviewed in the next section. In Section 3, a brief introduction of the CRN and SDN technologies is introduced. The overall properties and design stages of the proposed network together with related algorithms are explained comprehensively. Section 4 gives the simulation results. Finally, the last section concludes the paper.

## 2 Related works

A number of proposals have been found for SDN and CRN in the literature. However, there are a few studies on SDN-based CRN architecture. Some of these studies are explained below.

A study is proposed on OpenFlow-based CRN architecture (SD&R) in [4]. In their study, the authors introduce base stations with OpenFlow support and suggest software agents on base stations to provide radio situation report to the cognitive control function implemented in the controller. Although the study is quite inspiring, it differs from our study in terms of both evaluation parameters and the use of OpenFlow protocol, which is not energy efficient.

A study on an SDN approach is developed that makes spectrum agency for CRN in [5]. A cloud-based central controller is proposed for a flexible SDN-based CRN architecture, which has control over spectrum allocation for base stations. In addition, by configuring the appropriate flow rules in OpenFlow-based cognitive radio (CR) base stations, the controller can take actual information about network traffic status. With this information, the controller has traffic and channel aware spectrum analysis. The proposed architecture and spectrum allocation scheme are analysed through Mininet. As a result, their study shows five times more performance than the static spectrum allocation scheme. One of the main disadvantages of this study is the increased complexity with the developed algorithm. The main difference in our study is that the controller uses a channel bonding technique to meet the QoS requirements of CRN users.

In [6], the authors conduct a study on SDN architecture for CRN, and propose and build an SDN architecture prototype with OpenFlow (southbound protocol) for heterogeneous network spectrum sharing in the television white space. The controller approach for CRN and OpenFlow-enabled framework is analysed, and the implementation of the software-defined CRN prototype is done with the SDN controller and the long-term evolution/Wi-Fi network simulator. Also, the authors perform some basic control functions of the CRN and study CRNs based on new potential scenarios. The study is mostly handled as a prototype and performance analyses are not performed. In this context, our study also provides a performance analysis of SDN-based CRN architecture.

In [7], a study on software-defined CRN framework is performed. The authors propose a virtualisation-based SDN framework for CRNs. This approach uses the concept of multi-layered hypervisors for efficient resource management. It also suggests a non-centric control pattern that allows the CRN base station to transfer some of its management burdens to network users. CRN resource virtualisation enables dynamic, non-infrastructure, and efficient resource allocation for CRN users. Their proposed architecture reduces the dependence of CRN users on base stations and physical network resources and improves network performance by reducing the control load. In their study, only the overhead and throughput results are examined and other network performance parameters are not discussed.

In [8], a study on the development of SDN-based network management is performed. In addition, the infrastructure of the current network and the management structures to advance network management in various ways and to diagnose its problems are handled. Network management is concentrated on three issues; allowing for frequently changing network conditions, ensuring a high-level network configuration, providing network visibility, and better visualisation and control over tasks for problem resolution. The authors define technologies that allow their network operators to identify their networking principles through a high-level language in a wide range of environments and easily identify the source of performance problems. In addition, various prototype installations are proposed on the campus and home networks, and how SDN architecture enhances common network management tasks is shown in the study.

In [9], a study on the concept of software-defined mobile networks (SDMNs) is performed. By focusing on the software-defined model for radio access networks, the demands of the SDMN architecture are addressed. The authors investigate the main problems of architectural radio access networks presented as SDMN and present valid solutions for SDMN and standardisation activities. In the study, it is stated that CR technology would be beneficial on the spectrum sharing of SDMN architecture. However, the SDN approach is not integrated with CR technology.

In [10], the authors studied evolvable architecture for a software-defined wireless network (SDWN) and wireless personal area networks (WPANs). The advantages of the SDN architecture for wireless network environments with fewer infrastructures such as WPANs have been reviewed. A prototype application called SDWN, which provides a complete SDN solution for WPANs is developed in the study. With their study, the effect of the SDN approach on wireless communication is also investigated and becomes a useful model for software-defined CR (SDCR) architecture.

In [11], the authors make a comprehensive research on integrating the internet architecture of objects with the SDN approach and propose some solutions for different communication infrastructures. In addition, a critical review of the internet of things (IoT) and SDN technologies is conducted; the current trends in the research and the factors contributing to the futuristic impact are examined. The comparative analysis of the existing solutions for SDN-based IoT applications is expressed in an easy and concise manner. A study on SDN and network virtualisation for cloud computing was performed in [12]. Information about virtualisation reasons and advanced network technologies developed by various standards are presented. The study based on the SDN approach, which plays a key role in the network programmability context proposes a new virtualised session layer called open application delivery network.

In [13], a study on SDN controller placement is conducted. Since network problems lead to separate the control and forwarding planes, the authors develop various algorithms that can be used to maximise the reliability of the SDN to obtain informed placement decisions. Simulation results of the algorithms evaluated using real topologies show that the controller placement strategies are very important for the SDN performance and that a Greedy algorithm provides almost optimum results.

In [14], the QoS management and prioritisation with SDN issues are studied. It is suggested that SDN technology can be managed more flexibly by using the SDN paradigm of QoS by reducing the loss rate by 5% and the latency by more than 50%. Also, a software manager implementation developed specifically for SDN architecture is proposed.

As a result, there are very few studies in the literature suggesting the SDN-based CR approach. However, different studies are increasing day by day, in which SDN approach is integrated with various technologies. The differences in the SDCR architecture we proposed from the studies in the literature are as follows:

- SDCR architecture is proposed to support application-specific requirements of CRN.
- The real-time modification of the base stations and network topology functions is accomplished by the policy-based flow rules defined on the controller.
- Distributed control and management processes are important problems for CRN communications. To overcome these problems, all control and management functions are operated by the controller.
- The channel bonding technique is used to increase the performance of the network.


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- By transferring some control and management functions to the controller, the base station and SU overheads are reduced and energy consumption and delay ratios are reduced considerably.
- Riverbed Modeler simulation software was used for performance evaluation of SDCR.

## 3 SDN-based architecture for CRNs

SDN is a new network approach that enables the management of network resources more flexible and solves many problems existing in traditional network architecture [15, 16]. CR is a new network technology that provides effective, efficient, and dynamic use of limited and inefficient spectrum [17]. SDCR networks combine SDN and CR technologies for resulting in effective and efficient central cooperative spectrum usage. Thus, a network management policy on a virtualisation-based SDN approach is adopted for CRNs, and a CRN with a multi-layered controller is proposed to effectively and efficiently share network resources.

In CRNs, base stations have some management responsibilities. These responsibilities show that both the base stations are overloaded and the users increase their dependence on the base stations. To overcome these problems, a semi-distributed control system is proposed in this study, so some of the base stations' responsibilities are transferred to an SDN controller. With the proposed architecture, resource virtualisation for CR networks, dynamic, independent of the infrastructure, effective, and efficient resource allocation for CR users are provided. SDCR network architecture increases network performance by reducing control load on base stations and users, while CR network users are also less dependent on base stations and physical network resources [18].

### 3.1 Wireless CRN

The continuous increase in the use of wireless devices has also led to the problem of inefficient use of the limited spectrum [19–21]. Wireless networks and mobile devices use licensed and unlicensed spectrum. Users pay a price to use the licensed spectra, and they have priorities for the use of the spectra. Besides, unlicensed spectra can be accessed by everyone. Along with the IoT, many devices such as Wi-Fi, Bluetooth, remote control etc., increase the usage of unlicensed spectrum. Consequently, much data, audio, and real-time video traffics are generated and more bandwidth requirements increase day by day [22, 23].

Many frequency bands have been dedicated to different wireless applications [24, 25]. For future wireless applications, there are not enough available spectrum bands [26]. However, many studies reveal that a significant part of the spectrum is not fully utilised and the spectrum used is time and location-dependent [27]. The traditional network approach does not allow unlicensed users to utilise unused portions of the fixed spectrum allocated to individuals or services. However, for new applications, the scarcity of spectrum and the increase in unused portions of the spectrum reveals the dynamic spectrum allocation.

One of the main problems of today's wireless network infrastructure is that unlicensed spectrum can no longer respond to increasing demands [28]. However, many licensed spectra are not fully used. As a solution to this problem, some licensed spectra can be used by unlicensed users known as CR users [29, 30]. CR approach gives a perspective that allows a licensed spectrum to be used by users who do not have a license [28, 31]. CR has the ability to perceive the environment, is aware of other nodes or networks, adapts itself to changes in the environment, and has a learning process capability.

CR technology defines two types of users. One is primary users (PUs) (licensed users) and the other is SUs (unlicensed users) who can opportunistically access licensed spectrum in CR systems [31, 32]. An example of CRN is shown in Fig. 1. CR technology recommends dynamic spectrum sensing technology for the effective and efficient use of the spectrum. This approach provides dynamic spectrum access that enables the use of the 'smart' spectrum for existing holes in frequency bands [17, 19]. In CR technology, SUs perform periodic scanning and identification

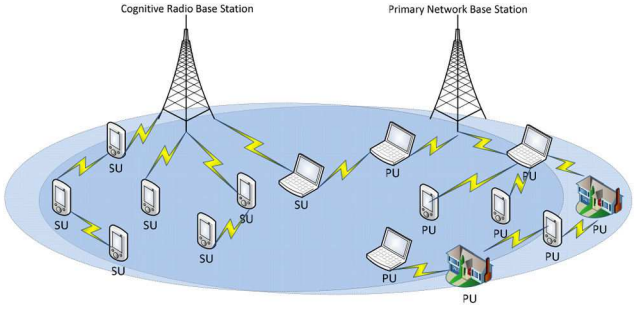



**Fig. 1** *Example of CRN architecture*

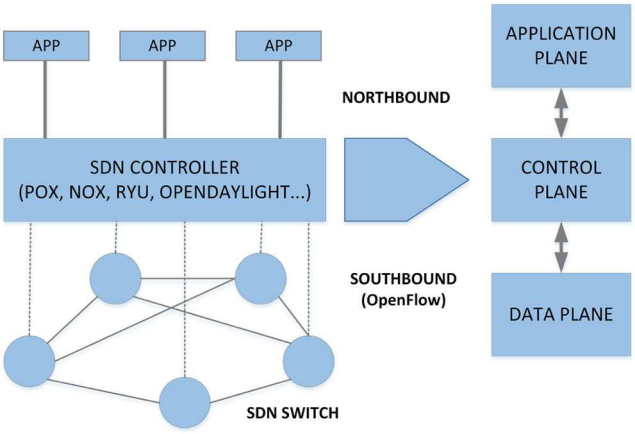



**Fig. 2** *Example of SDN architecture*

processes to detect available channels. The most important criterion in CR networks is that while the SUs use frequency bands, they certainly do not interfere with the communication of the PUs.

### 3.2 Software-defined networking (SDN)

SDN approach aims to remove the limitations of traditional network infrastructure, proposes the abstraction of control and data planes [33], and allows rapid adaptation of network and management systems [1, 34]. Thus, it provides a high performance, dynamic, efficient improvement network infrastructure with a control plane that can logically supervise the entire network from a central point [35, 36].

SDN architecture separates the control plane and forwarding functions from each other and the control plane is transferred to an application running on the server called the SDN controller. The controller is capable of managing network devices in the data plane. So, the controller manages the flow tables of all the switches existing on the network. It also gathers all the statistics about the network. In Fig. 2, SDN architecture can be seen. The SDN architecture comprises three planes named application, control, and data planes. The northbound interface provides communications between the application plane and control plane and also, the southbound interface connects the control plane and data plane [1, 2, 8].

### 3.3 SDN-based CRN architecture

In CRNs, it is necessary to determine the available licensed channels and to allocate them to the SUs considering the QoS requirements. The SUs need to provide initial communication with the controller and implement the initial setup. In CR networks, it is determined how the SUs affect the environment by taking into consideration the throughput, the delay, the packet loss rates, and the bit error rates (BERs) of the PUs. The proposed SDCR network architecture is shown in Fig. 3. In addition to that in Fig. 1, there is an SDN controller in the environment.

The sequence diagram of the SDCR is outlined in Fig. 4. The stages of the proposed scheme are as follows. The first stage (i) is the setup phase in the proposed approach. The other stages of the


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developed architecture are (ii) the controller detects the environment and determines the available channels; (iii) gives information to the SUs in the environment about controller; (iv) requests the appropriate channels from the controller by SUs and (v) allocates channels considering the packet sizes to the SUs. If there is not enough and available channel for the SUs requesting the channel, the SUs are not included in the network. The general operations at SUs are summarised in the flow diagram in Fig. 5.

The state diagram of the SU is shown in Fig. 6. Each state is expressed comprehensively as follows:

- The statistical information and nodes' specifications are determined and the system variables take initial values in the Int state machine. Values about time slots, mainframe time, first channel time etc., are allocated. Also, information about node is assigned from upper layer.
- The parameters are located to the packets from source and sent to the queue at the Queue state machine.
- The packet type is determined when the packet comes in the Received state machine. When the installation assignment packet arrives, the values such as channel information are allocated to the variables.
- Idle state machine is served as waiting for state while other state machines are passive.
- At the send state machine, when the necessary conditions are met, the sender transmits packets from the queue. Here, the channel detection is performed with the aid of the channel information allocated to the node, and the sending operation is performed.
- In the Hello state machine, the controller performs initial setup operations with hello message so it can communicate with the node. This is the first communication between the node and the controller.
- In the echo state machine, symmetrical control messages are sent and received periodically between the controller and the node.
- The error state machine is used to transmit communication problems that occur between the nodes and the controller.
- In the packet-in state machine, the nodes learn data traffic rules from the controller. The node has only controller information after the initial setup. The node requests channel information, base station information etc., in this state.

In addition to those states, in Fig. 7, the controller state transition diagram is presented.

- In the configuration state machine, the messages that are sent by the controller to the node are performed for configuration notification. If it is necessary, the controller performs the channel bonding according to the packet size. Also, the controller sends channel information to the node, and the flow table updating process is performed in this state.
- In the features state machine, there are messages that let the controller get information about the state of the node. The controller wants this information to every node that requests to connect to itself.
- In the sense state machine, the core operations of the CR network environment such as listening to the medium periodically to detect idle channels, temporarily storing the appropriate channels in demand or for the SUs to be found, and keeping channel utilisation statistics are executed.

In the CR network model based on the SDN approach, a new channel allocation scheme is designed to meet the QoS requirements. The channel allocation scheme allocates the required number of channels to the SUs according to the packet size. In this way, the guaranteed quality of data transmission will be ensured by providing the QoS requirement to nodes with different offered loads. Delay values are also reduced. The channel allocation mechanism reduces the packet loss ratio (PLR) value by avoiding packet collision. It also provides scalability of networks thanks to the controller.

The channel bonding technique is called the concatenation of neighbour channels for large packet sizes [36]. It also means that multiple channels are allocated to nodes with different packet sizes to meet QoS requirements. In this way, the nodes can send their data to the allocated channels and throughput is also increased. Fig. 8 shows the channel bonding mechanism. As can be seen from the figure, when the single channel is not sufficiently based on the packet size, more than one channel is allocated to meet the QoS requirements of SUs.

## 4 Simulation results

Riverbed Modeler is a simulation software that provides a virtual environment for modelling, analysis, and evaluation of network technologies, network infrastructures, and protocols. The nodes used in the proposed SDCR architecture, communication protocols,

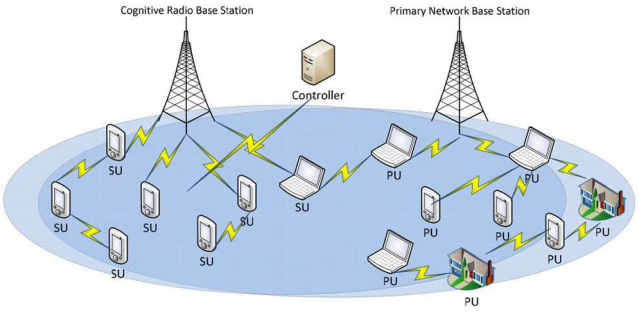



**Fig. 3** *Proposed SDCR network architecture*

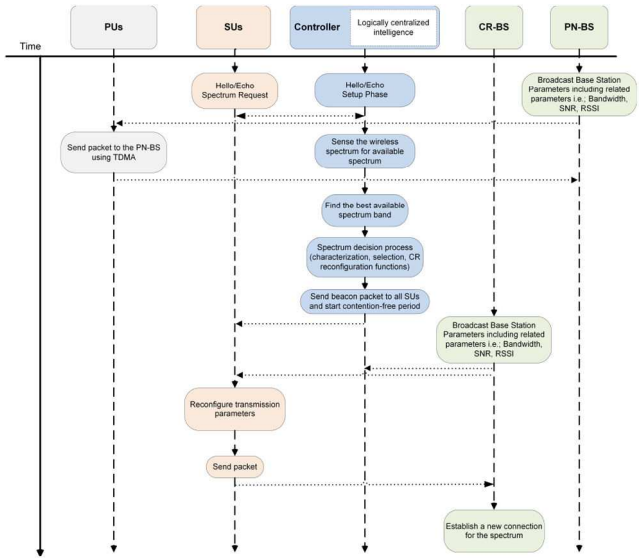



**Fig. 4** *Sequence diagram of the SDCR*

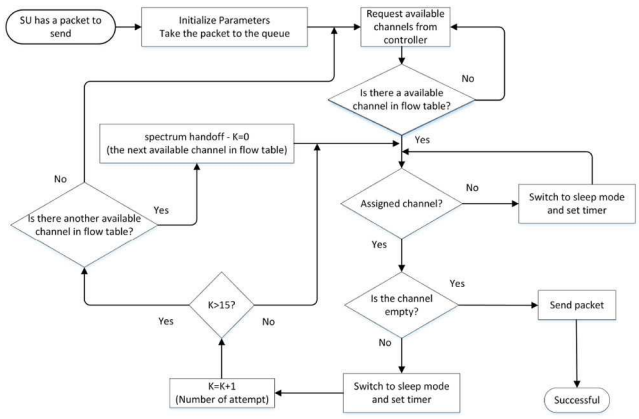



**Fig. 5** *Flow diagram of SU in the SDCR*




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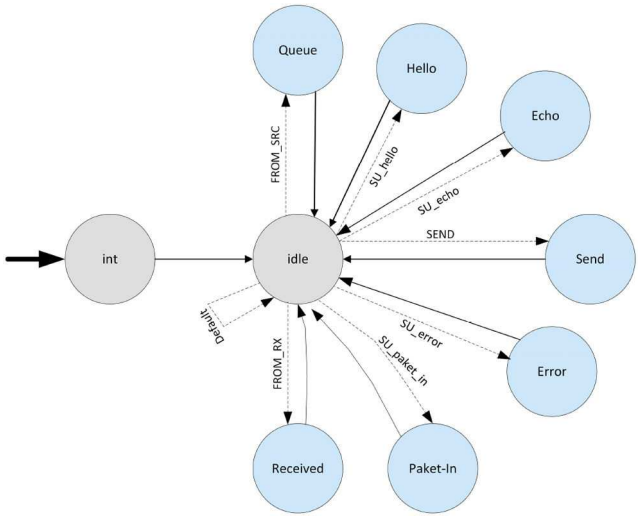



**Fig. 6** *State transition diagram for SU*

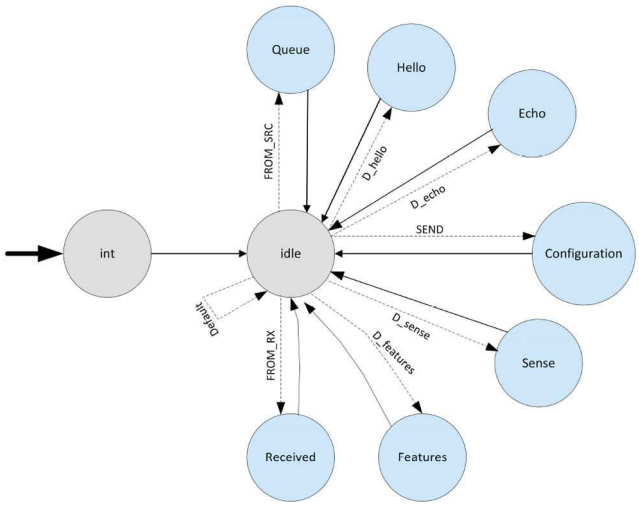



**Fig. 7** *State transition diagram for the proposed controller*

**Table 1** Simulation parameters

| Parameter | Value |
|---|---|
| simulation time | 3600 s |
| slot length | 100 ms |
| frequency of receiver and transmitter | 2.4–1.85 GHz |
| number of PU and SU | 10–5 |
| bandwidth of PU and SU | 2 MHz |
| modulation scheme | binary phase shift keying |
| transmit power of SU | 0.1 W |
| data rate of PU and SU | 1 Mbps |
| probability of detection | 0.91–0.99 |
| probability of false alarm | 0.01–0.09 |

and controller mechanism are designed with C-Proto language and performance analyses are performed on this discrete event simulation software [37].

The controller, PUs, and SUs in the SDCR network are modelled with Riverbed Modeler. There are ten PUs, five SUs, and two base stations (primary network base station and CR base station) for primary network and CRN, and one controller in the SDCR simulation model. All simulation parameters are shown in Table 1. End-to-end delays for the primary network, primary network delays for five SUs, and packet loss rates are investigated by selecting different offered loads for the SUs. Also, for the equal and different packet sizes, primary network throughput and proposed network architecture throughput are examined and

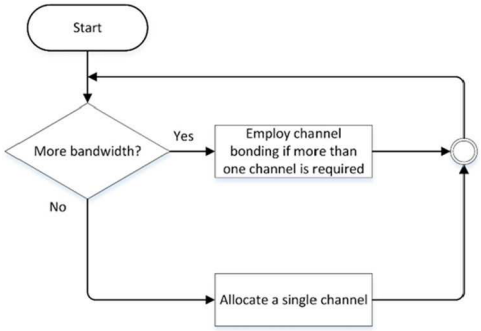



**Fig. 8** *Channel bonding mechanism*

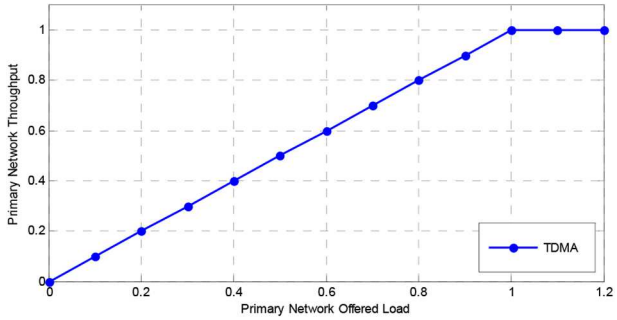



**Fig. 9** *Throughput values of the primary network*

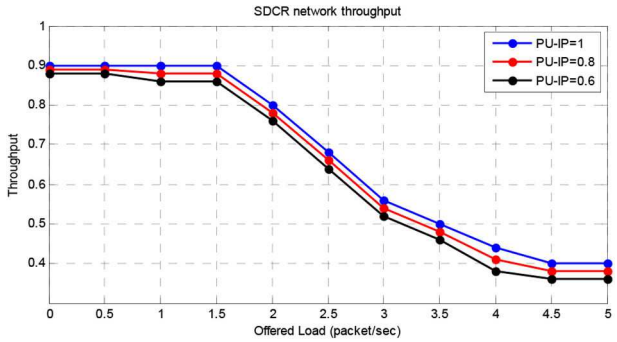



**Fig. 10** *SDCR network throughput (equal packets)*

network performance is improved by using channel bonding technique.

Throughput is one of the network performance metrics. It is defined as the ratio of the number of packets successfully received in a network environment to the total number of packets in a given time period. The number of packets offered to a network on a unit-time is called the offered load. Time-division multiple access (TDMA) protocol, which defines the time-slot of each user, is used for the primary network. Fig. 9 displays the primary network throughput of the TDMA technique under different network conditions (offered load). There are ten PUs in this network scenario. When the primary network offered load is increased from 0.1 to 1, the throughput also rises at the same rate. When the primary network offered load is 1 and the throughput remains the same. This is an expected result of the TDMA protocol and traditional CR architecture.

Fig. 10 shows the SDCR throughput values for different idle medium probabilities. The number of PUs is ten and the number of SUs is five in the simulation scenario. The PU-idle probability (PU-IP) is defined as the probability of no active PUs is in the environment. When the primary network throughput is the lowest, the SDCR throughput is the highest. In the case of PU-IP = 1 (means no active PU in the network), the SDCR throughput for all offered load values is the highest level. As PU-IP increases, the SDCR throughput decreases, and the total throughput is the highest level for all cases. As can be seen in Fig. 9, the highest throughput value is 0.9 where all SUs have equal packet size because of false alarm and sensing process in SDCR.


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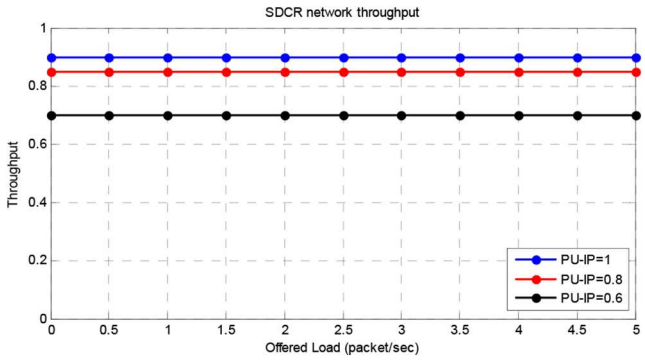



**Fig. 11** *SDCR network throughput (different packet sizes)*

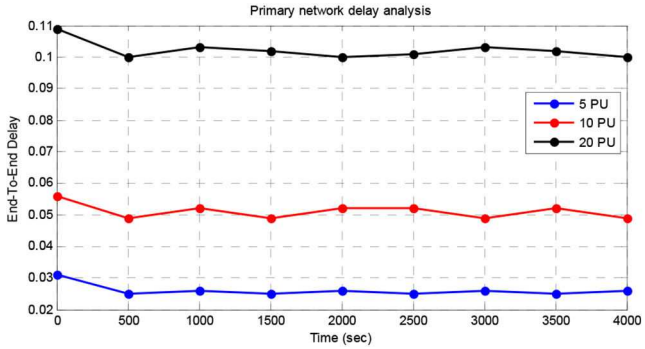



**Fig. 12** *Primary network delay analysis*

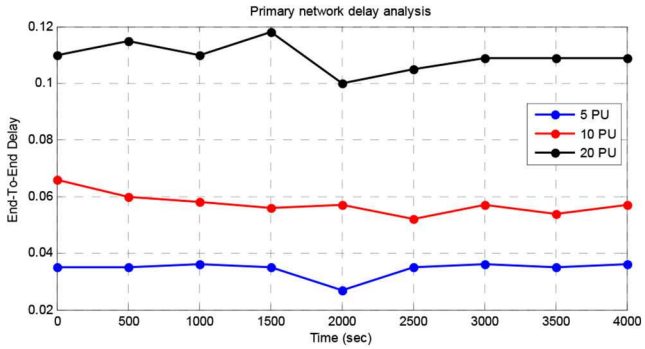



**Fig. 13** *Primary network delay analysis (five SUs with the equal packet size)*

Fig. 11 shows the SDCR throughput values for different idle medium probabilities. In this scenario, SUs have different packet sizes as two SUs have 50 kb; three SUs have 10 kb. The idle channels are determined by the SDN controller, the SUs apply to the SDN controller for using a channel. The controller performs the channel assignment by considering the QoS requirement according to the packet size of the SUs in the environment. In the case of PU-IP = 1, PUs throughput is the highest level for all offered loads. It is observed that the throughput does not decrease, despite the increasing offered load values compared with Fig. 10.

The controller has idle channel information, and it performs the channel assignment process considering QoS. In case there is no idle channel, SUs are kept waiting by the controller in order not to decrease the primary network throughput. One of the most important performance evaluation parameters used in simulating wireless architectures is the end-to-end delay. This parameter is expressed as the time it takes to get the last bit on the destination side of the packets when the first bit is generated on the source side. The primary network end-to-end delay results are shown in Fig. 12. According to the end-to-end delay results with different numbers of PUs (5, 10, and 20) in the scenario, when the number of users increases, it is observed that the delay increases slightly.

In Fig. 13, end-to-end delay results are shown for a scenario with five SUs and different numbers of PUs (5, 10, and 20). The SUs have equal packet size as 10 kb in this scenario. It is observed

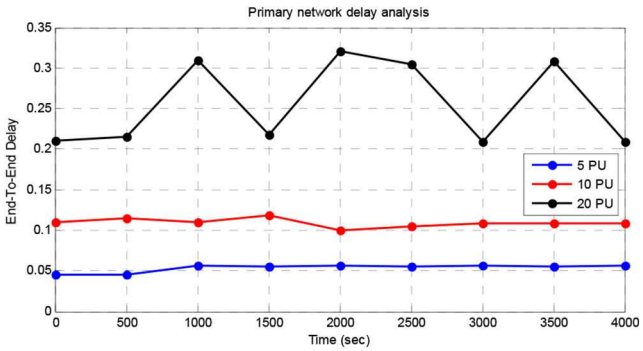



**Fig. 14** *Primary network delay analysis (five SUs with different packet size)*

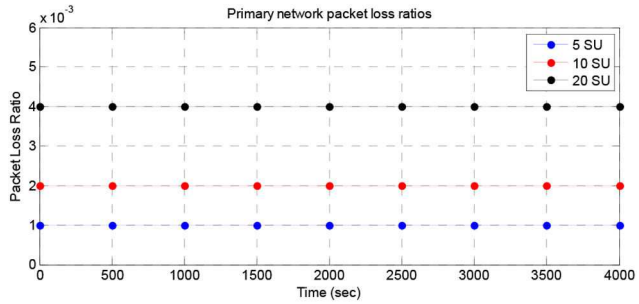



**Fig. 15** *Primary network PLR for the equal packet sizes*

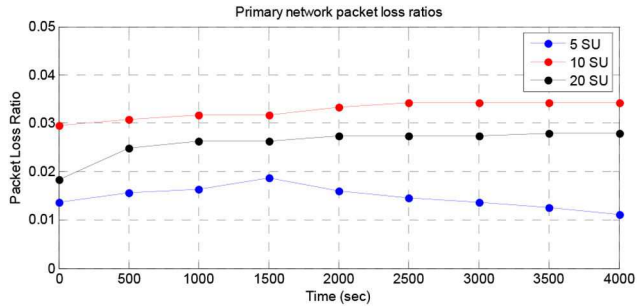



**Fig. 16** *Primary network PLR for different packet sizes*

that end-to-end delays increase as the number of PUs increases. End-to-end delays slightly change; this is an expected and desired condition in SDCR. End-to-end delay results are given in Fig. 14 where five SUs and different numbers of PUs (5, 10, and 20) are in the scenario. Two SUs have 50 kb packet sizes, and three SUs have 10 kb packet sizes. Similarly, it is observed that as the number of users increases in the scenario, the delays increase with the addition of the SUs with different and larger packet sizes. The controller in this scenario provides the QoS requirements of SUs by channel bonding technique. This technique does not negatively affect PUs communications as can be seen from the delay results.

In Fig. 15, the primary network PLRs are shown with ten PUs and different number of SUs (5, 10, and 20) in the same environment where all users have a packet size as 10 kb. As can be seen from figure, the minimum PLR is occupied with five SUs. The PLRs are increased with the increasing of the number of SUs. However, the PLR increase seems to be in very small quantities in this scenario.

In Fig. 16, the primary network PLRs are shown with ten PUs and different number of SUs (5, 10, and 20) in the same environment, where all users have different packet sizes. Two SUs have 50 kb packet size, and the other SUs have 10 kb packet size. As can be seen from figure, the minimum PLR is occupied by five SUs. The PLRs are increased with the increase of the number of SUs. The PLR is at the maximum level while the number of SUs is ten. The PLR decreases in the case of 20 SUs. The controller assigns fewer channels to the SUs in order not to damage the communication of the PUs.


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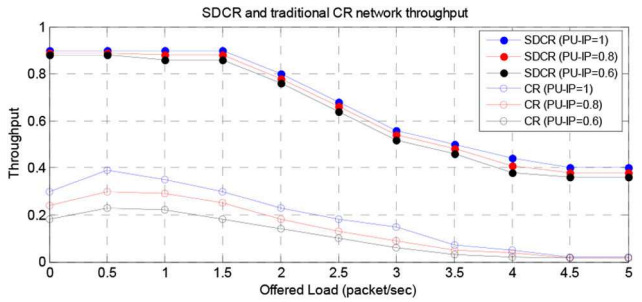



**Fig. 17** *Comparative analysis of SDCR and traditional CRN throughput*

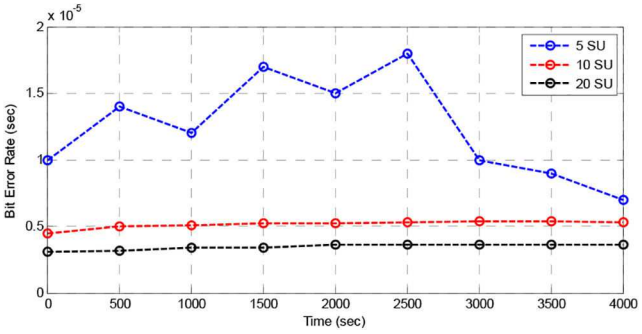



**Fig. 18** *Primary network BER*

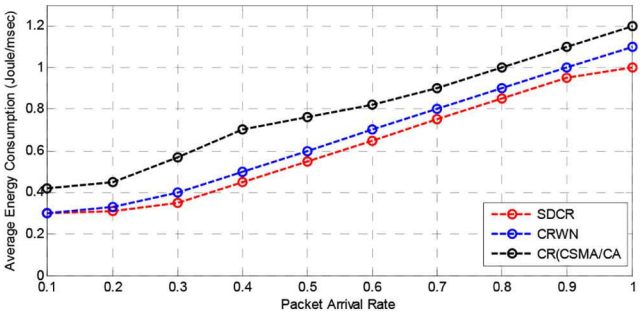



**Fig. 19** *Average energy consumption of SU node in comparative analysis*

The proposed SDCR architecture is compared with traditional CRN architecture (used slotted Aloha-based media access control) in terms of throughput in Fig. 17.

PU-IP values are selected as 1, 0.8, and 0.6, respectively, in the same scenario. The proposed SDCR architecture has a higher performance than the traditional CRN architecture. The SUs who want to use a channel get information about idle channels from the SDN controller, so, the primary and CRNs performances are improved. The SDN controller that coordinates and has all the information about the environment provides good performance for CRNs. In addition, the proposed architecture does not reduce the performance of both the primary and CRN environments by increasing the number of SUs in the environment, increasing the amount of offered load, or having different packet sizes.

In Fig. 18, the primary network BERs are given in the scenario with different numbers of SUs (5, 10, and 20) and ten PUs with different and large packet sizes. Two SUs try to transmit 50 kb data, while the other three SUs try to transmit 10 kb data. As can be seen from Fig. 18, the lowest BER is obtained when the number of SUs in the environment is 10 and 20. An increase in BER is observed with the decrease in the number of SUs. The main reason for this is that while there are five SUs in the environment, the traffic density is higher.

The controller limits the number of SUs to avoid damaging the communication of the PUs. This situation reduces the BER. When the BER results are analysed, it is seen that the increase in the number of users is at a level that will not cause problems for the primary network.

In Fig. 19, average energy consumption values of the SDCR, CR wireless network [17], and traditional CR architecture (with carrier sense multiple access with collision avoidance (CSMA/CA) protocol) for SUs are given comparatively. To make this comparison, it is assumed that ten PU and ten SU nodes communicate wirelessly. The SDCR architecture accomplishes better performance for all values of packet arrival rates. The main reason for this is that the other two approaches have distributed control mechanisms. On the other hand, the controller, which performs control, management, and coordination operations in the SDCR architecture, significantly reduces the workload of SU and base stations and also minimises the energy consumption values for SUs.

## 5 Conclusions

A new network architecture for CRN technologies based on the SDN approach is proposed in this study. By integrating the SDN approach, a controller for CRN environments is designed. Some tasks belonging to the CR base station are transferred to the controller. The performance analysis of the proposed network architecture is executed with the Riverbed Modeler software. With different offered loads for SUs, throughput results for the primary network and the CRN for the equal and different packet sizes are considered. The primary network end-to-end delays and primary network delays with five SUs and packet loss rates are also investigated. Furthermore, in our study, we improve the CRN performance by using the channel bonding technique. Moreover, we compare our proposed architecture with traditional CRN architecture with similar environment parameters and scenarios, and it is observed that the throughput increased by about 45%. As a result of this study, it is seen that the SDN approach provides good performance results for CRNs.

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