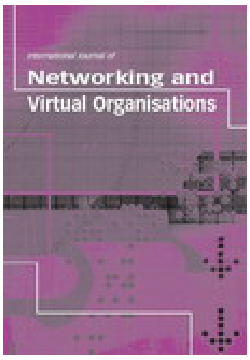

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T. Sarath Babu, Penke Satyanarayana, S. Nagaraja Rao

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Exploration of cognitive radio network with the integrated optimisation of channel allocation and power control by hybrid algorithm

T. Sarath Babu* and Penke Satyanarayana

Department of ECE,
KL Deemed to be University,
Vaddeswaram, Guntur, Andhra Pradesh, India
Email: tsarath@rediffmail.com
Email: penkesatyanarayana22@outlook.com
*Corresponding author

S. Nagaraja Rao

Department of ECE,
G. Pulla Reddy Engineering College,
Kurnool, Andhra Pradesh, India
Email: snagarajarao34@outlook.com

Abstract: Cognitive radio is one of wireless communications where the involving communication channels are detected through a transceiver. Spectrum allocation is a key challenge in the research on cognitive radio networks (CRNs). The conventional studies are focused on providing low-complexity solutions to find the power allocation to enhance energy efficiency and reduce the interference of the primary user and thus, satisfying the secondary users' minimum rate requirements. Thus, there is a need to introduce joint optimisation of channel allocation and power control in CRN. This is achieved by a new heuristic algorithm with the binary bat-reptile search algorithm (BB-RSA). This integrated mechanism is formulated by solving the multi-objective function regarding functions like throughput, outage probability, and Ergodic capacity. The heuristic algorithm is proposed to realise the best channel and power allocation in CRN. Extensive simulation results are presented to demonstrate the performance of the proposed scheme.

Keywords: cognitive radio networks; CRNs; channel allocation and power control optimisation; throughput; outage probability; Ergodic capacity; binary bat-reptile search algorithm; BB-RSA.

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Biographical notes: T. Sarath Babu is a research scholar in the Department of the Electronics and Communications Engineering, KL Deemed to be University, Vaddeswaram, Guntur, Andhra Pradesh, India. He received his BE degree in Electronics and Communications Engineering from Bangalore University, Bangalore, Karnataka, India in 2001. He obtained his MTech degree in Communications and Signal Processing from Sri Krishnadevaraya

University, Ananthapuramu, Andhra Pradesh, India in 2007. He has 15 years of teaching experience. His research interests focus on wireless communications and networks.

Penke Satyanarayana is a Professor in the Department of Electronics and Communications Engineering at KL Deemed to be University, Vaddeswaram, Guntur, Andhra Pradesh, India. He obtained his Master's degree (MTech) in Computers and Communication from JNTU, Kakinada in 2004 and PhD in MIMO Wireless Communications from JNTU, Kakinada, Andhra Pradesh, India in 2016. His research focuses are wireless communications and signal processing. He also published several research papers in international journals and conferences. He holds two patents published under his name.

S. Nagaraja Rao is a Professor in the Department of Electronics and Communications Engineering at G. Pulla Reddy Engineering College, Kurnool, Andhra Pradesh, India. He obtained his Master's degree (MTech) from J.N.T. University, Masab Tank, Hyderabad in Digital Systems and Computer Electronics in 1998 and PhD in Image Processing from JNTUA, Anantapuramu, Andhra Pradesh, India in 2011. His research interests focus in signal processing, image processing, and communication networks. He also published several research papers in international journals and conferences.

1 Introduction

CRN is ensured to reduce the problems regarding the spectrum congestion that is caused in next-generation networks since it has a unique overlay and underlay modes of communicating services (Wang et al., 2012). In the overlay node, unlicensed secondary users (SUs) get initiated to perform the spectrum handoff operations for moving toward other idle channels. At the same time, the licensed primary users (PUs) moved to their targeted channels. For preserving the quality of service (QoS) in both SUs and PUs, the spectrum handoff is required with two important operations (Lu et al., 2014). The first operation is to prevent interference by SU's timely decision to drop from the previous channels and, thus, to avoid the upcoming PU traffic (Zhang and Zhao, 2018a). The second operation is to select the effective target channel for minimising the degradation at handoff time. From the previous studies, it is revealed that resource allocation (RA) acts as the key factor for understanding the potentiality of CRN. So, a sizeable amount of work is done based on the RA concept (Zhang et al., 2019). On the other hand, there are some challenges of RA in CRN that are not still discussed in the existing studies, in which the development of RA problems based on the more-realistic consideration in CRN needs to be addressed (Pan et al., 2017).

If the PU gets arrives or any reduction in performance on the serving channel occurs, SUs have to stop their current transmission and perform the spectrum handoff that is changing to some other spectrum present at the similar or other CRNs (Kang et al., 2009). These interrupted SUs need to be designed with the optimal spectrum handoff method, which conserves the QoS. However, in the RA strategy, SU's transmit power present at the handoff target channel shows certain impacts on the transmission performance belonging to handoff SUs (Xiao et al., 2021). Most of the earlier studies are focused on the spectrum handoff problem or RA problem, and these two problems are raised in the multiple SUs scenarios when they perform the spectrum handoff simultaneously

(Awoyemi et al., 2016). The recent development of machine learning approaches is influenced to utilise in this problem as it has learning capacity concerning dynamic conditions. But, these works are in limited numbers and emerging state (Salameh et al., 2010). Further, the Q-learning technique has been developed for solving the spectrum handoff using the test-bed execution. However, a tradeoff occurs between timeliness and accuracy when designing the models and requires accurate prediction concerning the network states (Huang et al., 2013).

Recently, swarm intelligence algorithms are generally utilised for power control (Zhang et al., 2011). In underlay CRNs, an artificial fish swarm optimisation algorithm has been implemented to provide the SU's communication quality by considering the interference constraint of PU (Zhang and Zhao, 2018b), which has been aimed to reduce the total interference of the SU transmitter and PU receiver (Duggineni and Chari, 2017). But, the methods only focus on reducing the total interference, which cannot ensure the optimal quality of communication of PU. Further, a chaotic particle swarm algorithm (PSO) is for minimising the total transmission power of the SU transmitter and also for resolving the optimisation issues considering certain constraints like maximum permissible interference, maximum transmission power, and minimum signal-to-interference-plus-noise ratio (SINR) of PU (Ma et al., 2017). The energy requirement of PU needs to be reduced through this approach that provides normal communication (He et al., 2020). To ensure the minimisation of transmission powers of SU, a dynamic PSO is developed for adapting to the environment with dynamic communication (Tian et al., 2020). All the above-mentioned algorithms are useful for focusing o the single objective problem of power control in CRN (Yu et al., 2014), where the channel (Jose and Tamilselvan, 2015; Jose et al., 2013) allocation and power control as the multi-objective function is not considered. Therefore, it is necessary to design the CRN model with a multi-objective function considering both channel allocation and power control using the heuristic strategy.

The main contributions of the developed CRN model are mentioned as follows.

- To elevate the transmission performance among the PU and SU of CRN by considering the optimisation of channel allocation and power control using the hybridised heuristic algorithm.
- To integrate a hybrid algorithm named BB-RSA by combining the features of two superior algorithms to tune the channel allocation and power control variables for enhancing the throughput and ergodic capacity and minimising the outage probability among PU and SU in CRN.
- To estimate the efficiency of the developed CRN model with convergence analysis, comparative analysis based on objective constraints using various algorithms.

The rest of the segments of the developed model are described as follows. Segment 2 provides a discussion about the existing works on CRN. Segment 3 discusses the need to optimise channel allocation and power control in CRN. Segment 4 ensures the developed CRN model with multi-objective function. Segment 5 describes the proposed BB-RSA-based optimisation. Segment 6 made the analysis of obtained results. Section 7 concludes the developed model.

2 Literature survey

2.1 Related works

In 2017, Pan et al. have developed the power allocation method considering "orthogonal frequency division multiplexing-based CRN (OFDM-CRNs)". Here, the performance degradation was controlled by maximising the data rate of SUs, where the total power budget and maximum allowable interference of SUs were considered. Hence, a controller has been developed for switched affine system considering the state constraint. This highly robust controller design was done according to the linear matrix inequality and Lyapunov stability theory for improving the realisation of actual power allocation. The analysis outcomes have demonstrated the efficacy of the implemented approach when compared with other baseline algorithms.

In 2019, Chen et al. have investigated the issues concerning power control in CRNs. Here, a multi-objective function was developed through the optimisation for enhancing the throughput of SUs and PUs that was required to be satisfied the constraint on interference temperature of PU along with the communication quality and transmission power. Hence, an 'improved multi-objective particle swarm optimisation (IMOPSO) algorithm' was developed to achieve the objective. Further, an 'improved coevolutionary multi-objective particle swarm optimisation (ICMOPSO)' was implemented to enhance the boundary searching ability belonging to the power control scheme. Finally, the developed two optimisation models were evaluated and demonstrated the maximum throughput of the conventional PSO algorithms.

In 2020, Chakraborty and Sahaa have developed a new machine learning-based target channel sequence (TCS) allocation, and generation method for improving the performance of the multiple practical SUs presented with 'Voice over IP (VoIP) communication'. Here, the TCS generation was designed as a greedy technique and a fractional knapsack problem for choosing the optimal channels according to their conventional conditions. Further, the 'hidden markov model-bidirectional long short-term memory (HMM-BiLSTM)' was developed to protect VoIP interests by predicting channel eligibility. The experimental results have shown that the dynamic channel allocation has been achieved with minimum delay in handoffs and call drops.

In 2013, Liu et al. have implemented a new problem related to joint power and frequency allocation considering the decentralised CRNs using the spectrum resources. Initially, the interactions were designed among the decentralised CRNsss links and, further, a strategy learning approach that has been effective in integrating power pricing and multi-agent frequency strategy learning. The cost function of the developed method is effective in theoretical analysis. Further, the experimental analysis has confirmed that the enhanced throughput performance was achieved through the developed model.

In 2017, Awoyemi et al. have proposed resource allocation (RA) models, which have involved certain strategies like heterogeneity for CRN, where the overall networking has been analysed. Moreover, the relevance was established, and its implications were under diverse classifications belonging to the heterogeneous network for making RA formulations. Here, the weights were researched for various classes and their impacts on the network's performance. The complex RA problems were resolved with the solution method by attaining the lower complex reformulation in the heterogeneous CRN. The results show that a possible optimal solution was attained through the developed model in the heterogeneous CRN.

In 2016, Zhao have suggested a novel approach for addressing the channel access and RA problems on the overlay CRN, where every SU was held with the multi-channel spectrum sensing and also transmitted the identified energy towards the imperfect reporting channel, especially to its fusion centre. Furthermore, an access factor was integrated for describing the channel-asses mechanisms when considering both the non-cooperative and cooperative methodologies. Effective iterative algorithms were developed for handling the non-convex problems raised in both single and diverse CR systems by determining the hidden convexity that occurs in the optimisation problems. Various numerical analyses were made, and that has shown huge improvements in the developed strategy to the comparative strategy.

In 2016, Chai et al. have proposed RA and spectrum handoff strategy for solving the problems in handoff SUs among the heterogeneous CRNs. For attaining joint resource management between diverse CRNs, an enhanced architecture was developed, according to which the developed RA and spectrum handoff strategy was performed. Then, the transmission efficiency of the handoff SUs were considered for developing an optimisation problem for enhancing energy efficiency. Further, an iterative algorithm was developed for solving the nonlinear fractional optimisation problem. Diverse evaluations have been made to evaluate the efficacy of the model.

In 2012, Shi et al. have studied optimising the RA and detection threshold to enhance the total downlink capacity of SUs in the CRNs. The optimisation problem was generated with the aspect of three collections of variables such as power allocation, sub-carrier assignment, and detection threshold. Two different methods were developed that were offline and online schemes to find the optimal global solution. The effectiveness of the implemented scheme was undergone evaluation with different static threshold selection algorithms.

In 2018, Saravanan and Rangachar have proposed two protocols, network lifetime with Kaplan-Meier (NLKM) and network lifetime with non-parametric model (NLNPM), to estimate the network lifetime. Here, the developed model has been used to control the packets in the network. Moreover, the forwarding packets were eliminated with the help of a directional antenna, and the communication ranges were maximised due to the elimination of dead nodes. Consequently, the NLNPM was computed based on two thresholds of the dead node. Thus, the simulation outcome has revealed that the designed protocols have been utilised for enlarging the network lifetime.

In 2022, Katre and Thanuja have implemented a new optimisation method in CRN for optimising the accurate throughput, delay, and energy. Moreover, the suggested model was utilised for maximising the energy and throughput and also minimising the delay in the CRN network. Here, the software-defined radio (SDR) was improved for validating the results. Throughout the analysis, the designed model has attained enhanced performance while combining the other-state-of-art methods.

In 2018, Sanjeevi and Viswanathan have developed an efficient method to optimise the energy in the cloud. Here, the virtual machine (VM) was used for creating and validating the processing time of the cloud network. Moreover, the VM has been migrated from one host to the other host with the help of the Markov decision model. However, the suggested model was evaluated with the help of Cloudsim to improve the quality of the cloud network. The simulation result has evaluated that the designed model has attained enriched performance.

In 2019, Lin et al. have developed an efficient network coding (E-neco) based data transfer model for efficient data transmission and communication services. Here, the improved coding-based scheme was used to control the network protocols. The designed method has been developed for the future generation of services in the wireless communication network. Thus, the experimental outcome has shown that the developed method has attained better throughput and energy in the network.

In 2020, Baina et al. have proposed an effective model in critical infrastructure that was developed to improve communication in the network. Here, the PolyOrBAC framework was introduced to secure and address the problem in critical infrastructure. Moreover, effective control was taken place to maintain the control of its resources based on the internal security policy. However, this framework has been used in practical scenarios. The result analysis has shown that the proposed model has attained enriched performance.

2.2 Problem statement

Various channel allocation and power control strategies are developed in the existing CRN models discussed in Table 1. Distributed convex optimal method (Pan et al., 2017) is highly utilised for the realisation in CRNs and can solve the linear matrix inequality problem. On the other hand, it is challenging to make mathematical development for representing the approach. IMOPSO (Chen et al., 2019) improves the boundary-searching ability and diversity regarding power control. But, it suffers from global search ability and increases the computational cost. HMM-BiLSTM (Chakraborty and Misra, 2020) reduces call drops and handoff delays and provides high accuracy. Yet, it is affected by channel estimation errors. Strategy learning algorithm (Liu et al., 2013) minimised the information exchange and enhanced the throughput performance. Still, it generates a lower convergence speed that leads to an exchange of spectrum resources. Branch-and-bound (BnB) technique (Liu et al., 2013) requires fewer available resources for serving the SUs in the network. However, it generates high computational complexity when considering larger networks. Channel-access strategies (Zhao, 2016) attain better aggregate throughput on transmission among the SUs. Yet, it does not provide optimal concurrent transmission at all times. Lagrange dual method and the Kuhn-Munkres (K-M) algorithm (Chai et al., 2016) requires less signalling cost and lower power consumption for performing accurate channel estimation. At the same time, it does perform the spectrum handoff and power allocation for solving the fading channel scenarios. Offline and online algorithms (Shi et al., 2012) generates close-to-optimal solution considering less complexity and contains real-time capability in the online algorithm. Even though it achieves global optimisation, it is affected by the computation complexity in the offline algorithm. Considering these challenges in the existing works, it is decided to design the optimal channel allocation and power control model in CRN.

Table 1 Features and challenges of existing channel allocation and power control-based CRN models

Author	*Methodology*	*Features*	*Challenges*
Pan et al. (2017)	Distributed convex optimal method	• It is highly utilised to realise CRNs and can solve the linear matrix inequality problem.	• It is challenging to make mathematical development for representing the approach.
Chen et al. (2019)	IMOPSO	• It improves the boundary searching ability and also diversity regarding power control.	• It suffers from global search ability and increases the computational cost.
Chakraborty and Sahaa (2020)	HMMBiLSTM	• It reduces call drops and handoff delays and also provides high accuracy.	• It is affected by channel estimation errors.
Liu et al. (2013)	Strategy learning algorithm	• It minimised the information exchange and enhanced the throughput performance.	• It generates a lower convergence speed that leads to an exchange of spectrum resources.
Awoyemi et al. (2017)	BnB technique	• It requires fewer available resources for serving the SUs in the network.	• It generates high computational complexity when considering larger networks.
Zhao (2016)	Channel-access strategies	• It attains better aggregate throughput on transmission among the SUs.	• It does not provide optimal concurrent transmission at all times.
Chai et al. (2016)	Lagrange dual method and K-M algorithm	• It requires less signalling cost and lower power consumption for accurate channel estimation.	• It does perform the spectrum handoff and power allocation for solving the fading channel scenarios.
Shi et al. (2012)	Offline and online algorithms	• This generates a close-to-optimal solution considering less complexity and contains real-time capability in the online algorithm.	• Even though it achieves global optimisation, it is affected by the computation complexity in offline algorithms.

3 Necessity of optimal channel allocation and power control in cognitive radio network

3.1 Cognitive radio network routing

The CRN is a most significant model which helps to improve the utilisation of spectrum based on dynamically accessing the licensed spectrum of the PUs. In CRN, the data transmission requires an enhanced routing protocol for selecting the transmission path and also to minimise the consumption of power for transmitting the data. Numerous routing algorithms with high energy efficiency have been implemented in previous studies, where the development of 'mixed integer nonlinear programming (MINLP)' is effective in ensuring the optimal path through the consideration of certain constraints like routing, link capacity, and interference among the multi-hop CRNs. Following this method, the optimal path issues were identified and addressed by integrating the Hungarian algorithm for the multi-hop CRN. Recently, models have been developed considering the interfering effect caused by SU and PU subbands. These can be solved by implementing two probabilistic models that need to be uniform and triangular probability density functions. By observing the channel (Vinotha and Jose, 2019; Roy and Dutta, 2022) gains profile, power allocation is done with the help of spectral distance between the PU and SU subbands. Dijkstra's algorithm is incorporated for making the routing performance on the wireless networks by considering particular imperfect full-duplex nodes by analysing the one-hop interference and self-interference. It helps perform the joint route and power allocation to enhance the throughput among the wireless network by using the interference effect. On the other hand, this interference effect is required to be concentrated on the route selection. Further, the Bellman-Ford algorithm is developed to handle the problems of optimal routing for attaining high power minimisation and sum-power minimisation considering the multi-hop CRN. The joint selection between the communication routes and transmitting power allocation is performed to elevate the spectral efficiency of the optimal path. However, it does not involve the specific interference model, and so PU's interests are considered to be with less security. The routing and power allocation considering the multi-hop CRN is highly improved by certain constraints regarding interference. It is concluded that various routing algorithms are insufficient in providing better efficiency for multi-hop CRN when fulfilling the constraints regarding transmission and interference power.

3.2 Optimisation on channel allocation

The channel allocation issues are termed 0–1 integer programming problems by considering the decision variable (Rajkumar and Rebeiro, 2017; Rajkumar, 2022). Here, the simple approach named the exhaustive approach is utilised for tackling this problem by verifying the entire combinations between the variables 0 to 1 through the constraints at the objective function to find the optimal solution. Thus, the heuristic approaches are utilised, developed as BB-RSA to resolve the complex integer linear programming.

3.3 Optimisation of power control

The transmission is initiated with the PUs, SUs, and neighbouring SUs by considering the power variable optimisation. The previous studies assumed the power control problems are nonlinear and non-convex during the high signal-to-inference ratio (SIR) regime and, similarly, assumed that complex optimisation issues are highly challenging to transform into convex optimisation issues. During the lower SIR regime, some of the constrained nonlinear optimisation problems concerning the power control variable are impossible to change into tractable convex formulations, but that can be resolved by involving the heuristic approaches for determining the optimal solution using the reasonable convex approximation. Hence, the developed CRN model utilises the developed BB-RSA to tune the power control variable at both high and medium to lower SINR constraints.

4 Development of multi-objective function-based CRN with optimal channel allocation and power control mechanism

4.1 System model

Generally, the CRN is composed with two types of users such as primary and SU. Here, the licensed user is considered a PU and the unlicensed user is represented as a SU. Moreover, the SU mainly depends on the PU for transmitting the data. Here the key difference between the primary and SUs is shown here. The PU is only one user and the SU means more number of users. Here, the PU plays a significant role to transmitting the data to the SU. Here, the uplink channel bandwidth Y gets divided into M sub-channels, where the bandwidth is considered as 1 Hz for network computation. In addition, $\frac{Y}{M}$ is less when compared to correlation bandwidth between the channels and thus, making the channels in the form of flat fading. Simultaneously, N pairs of primary transmitter and receiver and similarly for SU are considered to be Qu_{Ur}/Qu_{Sr} and Tu_{Ur}/Tu_{Sr} at the system environment. The PU at m^{th} the location is regarded by $Qu_m(m \in \Phi_{Qu} = \{1, 2, \ldots, M\})$, and likewise, SU at k^{th} the location is termed by $Tu_k(m \in \Phi_{Qu} = \{1, 2, \ldots, M\})$. The channel allocation vector $Qu_m(m \in \Phi_{Qu} = \{1, 2, \ldots, M\})$ is taken as $D_m = \{d_{m1}, d_{m2}, \ldots, d_{mo}, \ldots d_{mO}\}$, in which o^{th} sub-channel $(o \in \Phi_{EO} = \{1, 2, \ldots, O\})$ is assigned for PU and the value considered for d_{mo} at the range of $\{0, 1\}$. The matrix D consists of entire channel allocation mechanisms about PU that are regarded as $D = [D_1, D_2, \ldots, D_m, \ldots D_M]^V$. Then, the PU is assigned to one channel, and thus, $O = M$ channels will be presented. The PU needs to occupy only one channel that as shown in equation (1).

$$\sum_{m=1}^{M} d_{mo} \leq 1, \forall m \in \Phi_{Qu} \tag{1}$$

$$\sum_{o=1}^{O} d_{mo} \leq 1, \forall l \in \Phi_{EO} \tag{2}$$

Further, the multiple SUs are transferring the spectrum to one PU. Here, the matrix $C = [C_1, C_2, \ldots, C_k, \ldots, C_n]^V$ represented in the channel allocation methodology for SU, and similarly, the channel allocation vector is regarded as $C_k = \{c_{k1}, c_{k2}, \ldots, c_{kl}, \ldots, c_{kN}\}$ that is obtained using the variable of channel allocation of PU. Consider the set of binary variables c_{mo} is valued to be 1, in which k^{th} SU ignores the channel k or else it needs to be fixed $c_{mo} = 0$. The variable that belongs to channel allocation c_{mo} has to be optimised to make it a constant variable. The network comprises M cognitive links, where all links are performed in interference with PU. The signal received Qu_m is denoted by QU_{Sr} that given in equation (3).

$$U_{Qu_m} = \begin{cases} n_0 & d_{mo} = 0 \\ \sqrt{r_{mo}} h_{mo} s_{mo} + m_0 + \underbrace{\sum_{i=1}^{N} \sqrt{r_{ko}} c_{ko} s_{mo} i_{ko}^{m}}_{Tu_k \ inerference\,to\,Qu_m} & d_{mo} = 1 \end{cases} \tag{3}$$

Here, the transmission power of k^{th} SU and k^{th} PU are correspondingly shown by r_{mo} and r_{ko}. The white Gaussian-based additive noise is represented n_0 with variance σ^2 as the mean value of 0. The link gain between the PU's receiver and transmitter is shown h_{mo}, and the interference link gain between the transmitter of SU and the receiver of PU is obtained i_{ko}^{m}. The information in the transmission between PU and SU is represented by s_{mo} and s_{mo}, respectively. The signal TU_{Sr} is depicted in equation (4).

$$U_{Tu_k} = \begin{cases} n_0 & c_{mo} = 0 \\ \sqrt{r_{mo}} h_{mo} s_{mo} + n_0 + \underbrace{\sqrt{r_{mo}} s_{mo} i_{mo}^{k}}_{Qu_m \ inerfernce\,to\,Tu_k} \\ \underbrace{\sum_{k=1}^{N} \sqrt{r_{ko}} c_{ko} s_{ko} i_{ko}^{m}}_{Tu_k \ inerference\,to\,Qu_m} & c_{mo} = 1 \end{cases} \tag{4}$$

Here, the term n_0 denotes the additive while Gaussian noise contains the variance σ^2 with a mean of value 0. The transmission power at m^{th} PU and o^{th} SU are correspondingly indicated by r_{mo} and r_{ko}. At the same time, the transmission data information Qu_m is indicated by s_{mo} and for Tu_k is expressed by s_{ko}. The transmission gain link at o^{th} the channel is denoted by c_{ko}, and the interference link gain is depicted by i_{ko}^{m}. The signal Tu_{Sr_k} is designed mathematically as in equation (5).

$$Tu_{Sr_k} = \begin{cases} n_0 & c_{ko} = 0 \\ \sqrt{r_{mo}} h_{mo} s_{mo} + n_0 + \underbrace{\sqrt{r_{mo}} s_{mo} i_{mo}^{k}}_{Qu_m \ inerfernce\,to\,Tu_k} \\ \underbrace{\sum_{l=1 l \neq k}^{N} \sqrt{r_{lo}} c_{lo} s_{lo} i_{lo}^{k}}_{Tu_k \ inerference\,to\,Qu_m} & c_{ko} = 1 \end{cases} \tag{5}$$

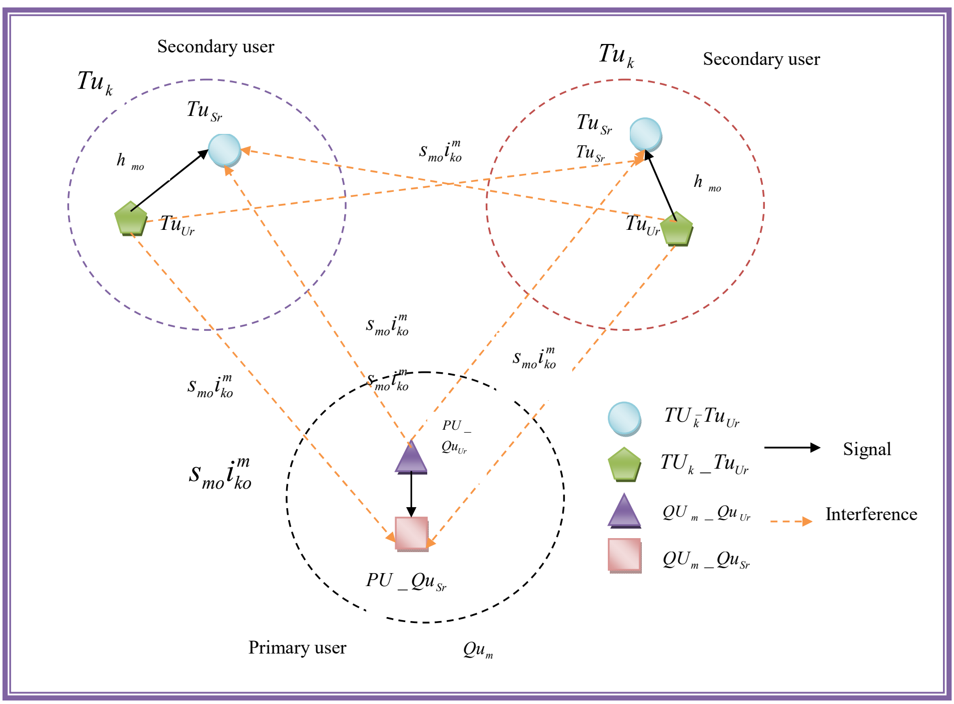
In equation (5), the term h_{ko} indicates the transmission link, and the terms i_{mo}^{k} and i_{lo}^{k} denotes the interference link of PU and SU from the receiver to the transmitter, respectively. The transmitted data from l^{th} SU is indicated by r_{lo}, which is considered as the neighbouring user of k^{th} SU and $k \neq l \in \Phi_{Tu}$. According to the above observations, the SINR of Qu_m and Tu_k are depicted in equation (6) and equation (7), respectively.

$$\gamma_{Qu_m} = \frac{r_{mo} h_{mo}}{\underbrace{\sigma^2 + \sum_{k=1}^{N} r_{ko} c_{ko} \left| i_{ko}^{m} \right|^2}_{noise\ power\ and\ Tu\ interference\ power}} \tag{6}$$

$$\gamma_{Tu_k} = \frac{\left| h_{ko} \right|^2 r_{ko}}{\underbrace{\sigma^2 + \left| i_{mo}^{k} \right|^2 r_{mo} + \sum_{l=1 l \neq k}^{N} r_{lo} c_{lo} \left| i_{lo}^{k} \right|^2}_{noise\ power,\ Tu_k\ inerference\ to\ Qu_m}} \tag{7}$$

Here, the term σ^2 indicates noise power, which will be equivalent for all the users in the network. The system model for channel allocation and power control is shown in Figure 1.

Figure 1 System model for the designed optimal channel allocation and power control in CRN (see online version for colours)



In this system model, the primary and SU is taken in the CRN model. Here, one PU Qu_m is considered, and more than one SU Tu_k is taken. Additionally, the SU mainly depends on the PU. Here, the data is sent from the PU to the SU. The PU makes the effective and reliable transmission in CRN.

4.2 Objective model

The developed CRN model considers the multi-objective function by tuning the variables of channel allocation and power control with the help of the proposed BB-RSA to maximise the throughput TrP and ergodic capacity ErC and to minimise the outage probability, OtP as shown in equation (8).

$$on_{fc} = \underset{\{c_{ko}, r_{ko}\}}{\arg\min} \left(\frac{1}{TrP} + OtP + \frac{1}{ErC} \right) \tag{8}$$

Here, the terms c_{ko} and r_{ko} are denoted as the optimal channel allocation and power control variables at the matrix C and R of SUs. The transmit power of SU is described by $R = [R_1, R_2, \ldots, R_k, \ldots R_N]^V$, and the respective power control vector is expressed by $R_k = \{r_{k1}, r_{k2}, \ldots, r_{ko}, \ldots, r_{kO}\}$. Here, some constraints are depicted in the following equations for performing the multi-objective function.

$$\left(\sum_{k=1}^{N} c_{ko} d_{mo} r_{ko} i_{ko}^{m} \right) \kappa^{-1} \leq K^{th}, \forall m \in \Phi_{Qu}, l \in \Phi_{EO} \tag{9}$$

$$r_{ko} \leq r_o^{mx}, \forall k \in \Phi_{Tu}, l \in \Phi_{EO} \tag{10}$$

$$r_{ko} \leq r_o^{mx}, \forall k \in \Phi_{Tu}, l \in \Phi_{EO} \tag{11}$$

$$R_{ot}^{Tu} \leq \varepsilon, \forall k \in \Phi_{Tu}, l \in \Phi_{EO}, m \in \Phi_{Qu} \tag{12}$$

$$c_{ko} = \{0,1\}, \forall k \in \Phi_{Tu}, o \in \Phi_{EO} \tag{13}$$

The outage probability and channel allocation-based constraints are depicted in equation (12) and equation (13), respectively. Further, the total power at SU is set as the constraint in equation (11). term Tu_k is restricted to exceed the maximum power r_o^{mx} for o^{th} channel transmission as mentioned in equation (10). Equation (9) denotes the interference temperature-based constraint.

5 Developed BB-RSA-aided optimal channel allocation and power control in CRN

5.1 Proposed B-RSA

The developed optimal channel allocation and power control in CRN implement the superior heuristic algorithm named BB-RSA for optimising the channel allocation and power control variables to enhance the transmission performance in CRN. RSA is chosen in this model since it can perform a strong global search. But, it causes premature convergence and is affected by local search problems. It also leads to disequilibrium issues between global and local searches. Hence, BBA is involved into developed BB-RSA as it gives superior convergence performance. In the proposed BB-RSA, if the condition $\left(tn \leq \frac{TN}{4} \right)$ is satisfied, then the BBA-based position update takes place, which is replaced by high walking approach.

RSA (Seyedali Mirjalili and Mirjalili, 2014) is a heuristically developed algorithm based on the characteristics of crocodiles. This algorithm follows the exploration and exploitation of the global and local search, respectively. This algorithm consists of three phases such as 'hunting, encircling, and social behaviour', which is derived from the behaviours of the crocodiles.

- *Encircling phase or exploration phase*: RSA algorithm updates the solution initialised from exploration to end up with exploitation by assigning the iterations into four modules. The search regions have to be computed to find better solutions based on two approaches, belly searching, and the high walking method. Consider the high walking approach, where the condition $\left(tn \leq \frac{TN}{4}\right)$ is required to be fulfilled in the conventional RSA. But, in the proposed BB-RSA, if this condition is satisfied, then the position update takes place with the BBA-based mechanism. Further, the conditions like $\left(tn \leq 2\frac{TN}{4}\right)$ and $\left(tn > \frac{TN}{4}\right)$ are required to be satisfied for performing the belly search approach as given in equation (14).

  $$z_{(p,q)}(tn+1) = Bs_q(tn) \times z_{(Rr1,q)} \times EV(tn) \times rd \tag{14}$$

  Here, the random parameter is indicated by β that is values as 0.1. The best solution is represented by $Bs_q(tn)$, and the random number is expressed by rd. The random position is taken into consideration, and it is indicated by $z_{(Rr1,q)}$. The parameter for evolutionary sense is denoted by $EV(tn)$ that is computed as shown in equation (15).

  $$EV(tn) = 2 \times Rr_3 \times \left(1 - \frac{1}{TN}\right) \tag{15}$$

  The small valued variable is indicated by ε.

- *Hunting phase or exploitation phase*: Here, two strategies named "hunting coordination and hunting collaboration" are involved based on the hunting characteristics of crocodiles in the exploitation phase. If the conditions $\left(tn \leq 3\frac{TN}{4}\right)$ and $\left(tn > 2\frac{TN}{4}\right)$ are fulfilled, then the hunting strategy with coordination is utilised for a position update. At the same time, if the conditions ($tn \leq TN$) and $\left(it > 3\frac{IT}{4}\right)$ are fulfilled, then the hunting strategy with cooperation is used for updating the position. These are mathematically depicted in equation (16).

  $$z_{(p,q)}(tn+1) = \begin{cases} Bs_q(tn) \times pdf_{(p,q)} \times rd & tn \leq 3\frac{TN}{4}\, and\, tn > 2\frac{TN}{4} \\ \begin{array}{l} Bs_q(tn) - \eta_{(p,q)}(tn) \\ \times \varepsilon - A_{(p,q)}(tn) \times rd \end{array} & tn \leq TN\, and\, tn > 3\frac{TN}{4} \end{cases} \tag{16}$$

$$A_{(p,q)} = \frac{Bs_q(tn) - z_{(Rr2,q)}}{Bs_q(tn) + \varepsilon} \tag{17}$$

$$\eta_{(p,q)} = Bs_q(tn) \times pdf_{(p,q)} \tag{18}$$

The percentage difference between the best and current solution is indicated $pdf_{(p,q)}$m and the hunting parameter is depicted by $\eta(a,b)$ that is computed in equation (18). The reduce function is represented by $A_{(p,q)}$, which is measured through equation (17).

BBA (Seyedali Mirjalili and Mirjalili, 2014) is derived from the original Bat Algorithm (BA) for solving the problems on multicast routing in the discrete binary space. The main strategy is to upgrade the position of the solution based on their probability towards their velocity. Hence, a transfer function is utilised along with the Binarisation approach. In the transfer function, the position of the solution changes towards the vector from 0 and 1, which makes the bat propagate onward the binary space. The V-shaped transfer function is employed, as shown in equation (19).

$$X\left(x_{ab}^{tn}\right) = \left|\frac{2}{\pi}\arctan\left(\frac{2}{\pi}x_{ab}^{tn}\right)\right| \tag{19}$$

Here, the term x_{ab}^{tn} indicates the velocity belongs to a^{th} the bat present at b^{th} the dimension. This produces the results between the real number between 0 and 1. The Binarisation operation takes place, which generated the position update value to be 0 and 1. This Binarisation approach can be written as in equation (20).

$$z_{ab}^{tn+1} = \begin{cases} \left(z_{ab}^{tn}\right)^{-1} & if\ rsd(\,) \le X\left(x_{ab}^{tn+1}\right) \\ z_{ab}^{tn} & f\ rsd(\,) \ge X\left(x_{ab}^{tn+1}\right) \end{cases} \tag{21}$$

Here, the term z_{ab}^{tn} indicates the location of a^{th} the bat present at b^{th} dimension. The pseudo-code of the implemented BB-RSA is depicted in Algorithm 1.

Algorithm 1 Implemented BB-RSA

Initiate the population size for both BBA and RSA
Generate the solutions Z
While ($tn < TN$)
    Fitness computation for all solutions
    For all solutions
        If $\left(tn \le \frac{TN}{4}\right)$
            Position update with BBA using equation (21)
        Else if $\left(tn \le 2\frac{TN}{4}\ and\ tn > \frac{TN}{4}\right)$
            Position upgrade using equation (14)
        Else if $\left(tn \le 3\frac{TN}{4}\ and\ tn > 2\frac{TN}{4}\right)$

Position upgrade using the first constraint of equation (16)

Else if $\left(tn \leq TN \text{ and } it > 3\frac{IT}{4} \right)$

Position upgrade using the second constraint of equation (16)

End if

End for

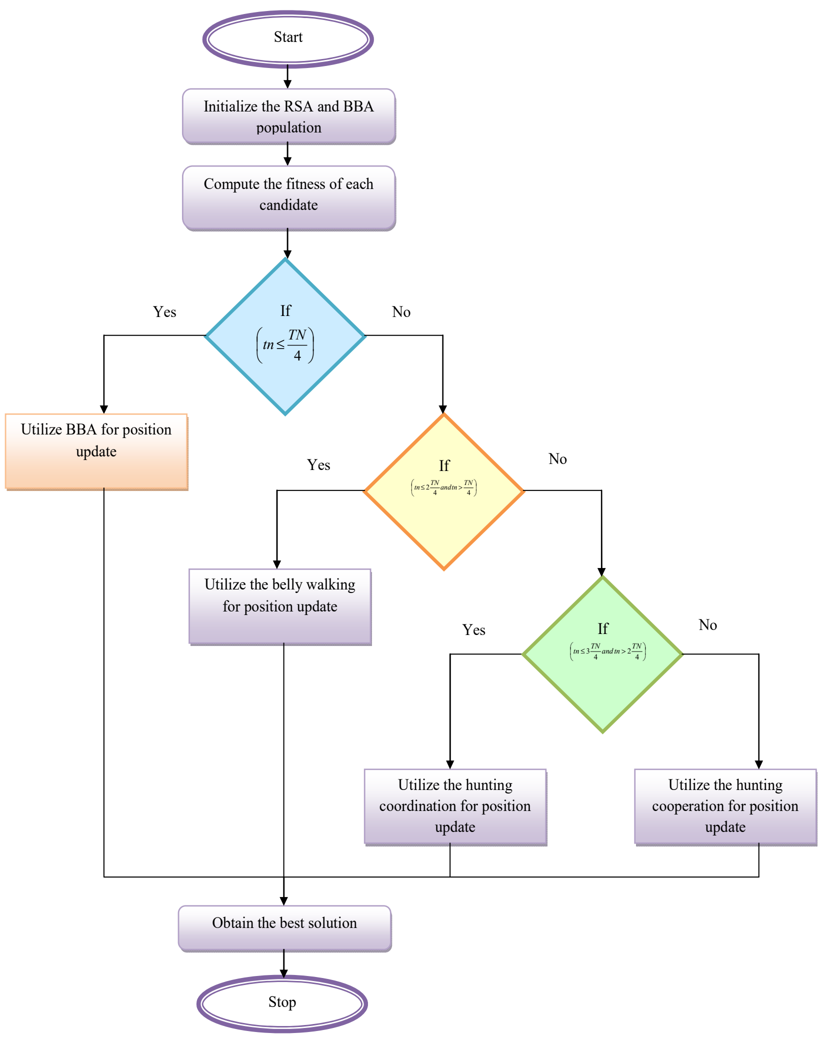
$(tn = tn + 1)$

End while

Return the best solution

The flowchart of the developed BB-RSA is depicted in Figure 2.

Figure 2 The diagrammatic representation of the designed method (see online version for colours)



5.2 Throughput

The system throughput is defined as "the average number of data frames precisely transmitted through destination in the one-time slot, in which the average discrete time Markov chain (DTMC) model in the source state that can be similar to the steady state probability of state source". The robust probability regarding the state source is expressed π_{Sr}, and the steady state in 3-D DTMC mode is indicated $\pi = \left(\pi_{Sr}, \pi_1, \cdots, \pi_f\right)$. Throughput π_{Sr} is presented as a binary function of P and W that is formulated as

$$\begin{cases} \pi \cdot pm = \pi \\ \sum \pi = 1 \end{cases},$$

where the probability matrix is indicated by pm belongs to the state transition that is acquired through

$$\left[(P+1) + G\sum_{l=1}^{P-1} l\right] \times \left[(P+1) + G\sum_{l=1}^{P-1} l\right]$$

Additionally, the throughput $TrP \leftarrow \pi_{Sr}$ is determined through equation (22).

$$TrP = \pi_{Sr}(P,W) = \frac{1 - fi(P,W)}{FI(P,W)} \tag{22}$$

The binary function (P, W) is expressed by $fi(P, W)$, and the error rate is depicted by $FI(P, W)$ computed through the following mathematical equations.

$$\begin{aligned} fi(P,W) &= \begin{cases} OtP_{SrM_{1,0,0}} \cdot OtP_{M_{1,0,0}DF} & \\ + \sum_{r=1}^{W} OtP_{SrM_{1,r,0}} \cdot OtP_{M_{1,p,0}DF} & P = 2 \\ Eq.(25), & P \geq 3 \end{cases} \\ fi(P,W) &= \begin{cases} OtP_{SrM_{1,0,0}} \cdot OtP_{M_{1,0,0}DF} & \\ + \sum_{r=1}^{W} OtP_{SrM_{1,r,0}} \cdot OtP_{M_{1,p,0}DF} & P = 2 \\ Eq.(25), & P \geq 3 \end{cases} \end{aligned} \tag{23}$$

$$FI(P,W) = \begin{cases} 1 + OtP_{SrM_{1,0,0}} + \sum_{r=1}^{W} OtP_{SrM_{1,r,0}} & P = 2 \\ Eq.(26) & P \geq 3 \end{cases} \tag{24}$$

$$\begin{aligned} fi(P,W) = {} & OtP_{SrM_{1,0,0}} \cdot \prod_{k=1}^{P-2} \left[OtP_{M_{j,0,0}N_{k+1,0,0}} \right] \cdot OtP_{M_{S-1,0,0}DF} \\ & + \sum_{r=1}^{W} OtP_{SrM_{1,r,1}} \cdot \prod_{k=1}^{P-2} \left[OtP_{M_{k,r,l}M_{k+1,r,l+1}} \right] \cdot OtP_{M_{P-1,r,P-1}DF} \end{aligned} \tag{25}$$

$$+\sum_{r=1}^{W}\left(\begin{array}{c} OtP_{SrM_{1,0,0}} \cdot \prod_{j=1}^{W_M^r-2}\left[OtP_{N_{j,0,0}N_{j+1,0,0}}\right] \\ \sum_{W_M^r=2}^{P-1} \cdot OtP_{M_{W_M^r-1,0,0},M_{W_M^r-1,r,1}} \\ \cdot \prod_{K=W_M^r,L=1}^{k=P-2,j=P-W_M^r-1}\left[OtP_{M_{k,r,l}M_{k+1,r,l+1}}\right] \cdot OtP_{M_{P-1,r,P-W_M^r}DF} \end{array}\right) \quad W \geq 3$$

$$FI(P,W) = \begin{array}{l} FI(P-1,W) + OtP_{Tr_{1,0,0}} \cdot \prod_{i=1}^{R-2}\left[OtP_{N_{j,0,0}N_{j+1,0,0}}\right] \\ +\sum_{r=1}^{W} OtP_{SrM_{1,r,1}} \cdot \left[OtP_{M_{k,r,l}M_{k+1,r,l+1}}\right] \qquad P \geq 3 \\ +\sum_{q=1}^{S}\left(\begin{array}{c} \sum_{W_M^r=2}^{W-1} OtP_{SrM_{1,0,0}} \cdot \prod_{k=1}^{W_M^r-2}\left[OtP_{M_{k,0,0}M_{k+1,0,0}}\right] \cdot \\ OtP_{M_{\left(W_M^r-1\right),0,0}M_{W_M^r,r,1}} \\ \prod_{k=W_M^r,L=1}^{k=P-2,l=P-W_M^r-1}\left[OtP_{M_{k,r,l}M_{k+1,r,l+1}}\right] \end{array}\right) \end{array} \tag{26}$$

Thus, throughput is acquired on equation (22) by deriving equation (23) to equation (23).

5.3 Ergodic capacity

The ergodic capacity of the CRN is computed through equation (27).

$$ErC \underline{\underline{\Delta}} \, C\left(\ln(1+SINR)\right) \tag{27}$$

Here, the ergodic capacity is determined through the pilot training sequence approach. The ergodic capacity at k^{th} SU is depicted by equation (28).

$$ErC \underline{\underline{\Delta}} \, C\left(\ln\left(1+\gamma_{Tu_k}\right)\right) \tag{28}$$

Here, the term γ_{Tu_k} denotes the SINR of SU that is computed in equation (7).

5.4 Outage probability

It is required to ensure the QoS of the CRN when the "user instantaneous rate Y_k is higher than the minimum rate Y^{th} of the system" to perform normal communication. If it is not estimated at the above-mentioned condition, it affects normal transmission. The outage probability is estimated by counting the number of interrupt events in the network. The system model involves the outage probability caused by SU. Hence, the outage probability is indicated in equation (29).

$$OtP^{su} = PR\left(Y_k < Y_{th}\right) \leq \varepsilon \tag{29}$$

Here, the term ε indicates the higher threshold targeted for the outage probability, which is $0 \leq \varepsilon \leq 1$. Equation (29) and equation (7) it is derived from equation (30).

$$PR\left[c_{ko} \log_2 \left(1 + \frac{\left|h_{ko}\right|^2 r_{ko}}{\sigma^2 + \left|i_{mo}^k\right|^2 r_{mo} + \sum_{l=1\, l\neq k}^{N} r_{lo} c_{lo} \left|i_{lo}^k\right|^2} \right) < Y_{th} \right] \tag{30}$$

The above equation can be simplified as in equation (31).

$$\sigma^2 + \left|i_{mo}^k\right|^2 r_{mo} + \sum_{l=1\, l\neq k}^{N} r_{lo} c_{lo} \left|i_{lo}^k\right|^2 = \theta \tag{31}$$

Equation (32) is obtained by deriving equation (30).

$$PR\left[c_{ko} \log_2 \left(1 + \frac{\left|h_{ko}\right|^2 r_{ko}}{\theta} \right) < Y_{th} \right] = PR\left[\left|h_{ko}\right|^2 \leq \frac{\left(2^{\frac{Y_{th}}{c_{ko}V}} - 1 \right) * \theta}{r_{ko}} \right] \tag{32}$$

Here, the random exponential distribution is developed by considering the channel to be a Rayleigh fading channel with the average value assumed to be 1, and further, the outage probability of SU is depicted in equation (33).

$$\begin{aligned} OtP^{su} &= \int_0^{\left(2^{\frac{Y_{th}}{c_{ko}}} - 1\right) * \theta} \exp\left(-\left|h_{ko}\right|^2 \right) e_{h_{ko}} \\ &= 1 - \exp\left[-\frac{\left(2^{\frac{Y_{th}}{c_{ko}}} - 1 \right) * \theta}{r_{ko}} \right] < \varepsilon \end{aligned} \tag{33}$$

Here, the appropriate value for outage probability is highly relied on the activity of SU as well as on fading channel statistics, which needs to be changed accordingly in a periodical manner.

6 Results and discussions

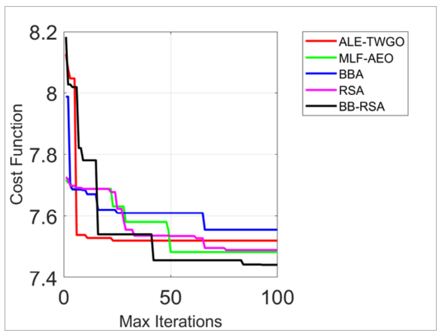
6.1 Experimental setup

The developed CRN model with the optimisation of channel allocation and power control using the developed BB-RSA utilised 'MATLAB 2020a' as their implementation platform. The efficacy estimation regarding the performance of the optimisation was conducted with several existing algorithms. The evaluation was made with a population of 10 and a number of 100 as the maximum iterations. The developed BB-RSA was compared with 'ALE-TWGO (Sarath Babu, 2022a), MLF-AEO (Sarath Babu, 2022b), BBA (Seyedali Mirjalili and Mirjalili, 2014) and RSA (Abualigah et al., 2022)'.

6.2 *Convergence analysis on the developed model*

The convergence evaluation was made on the implemented CRN model with developed BB-RSA to ensure the effective channel allocation and power control as shown in Figure 3. The developed algorithm achieves minimum cost function when increasing the iteration count that shows maximum throughput and ergodic capacity was attained with minimum outage probability among the PU and SU on data transmission. The implemented model secures 12.3%, 14.5%, 12.7%, and 11.2% better cost functions than ALE-TWGO, MLF-AEO, BBA, and RSA, respectively. This confirmed the convergence performance of the developed model.

Figure 3 Convergence evaluation on proposed BB-RSA-based optimal channel allocation and power control strategy in CRN (see online version for colours)



6.3 *Ergodic capacity analysis*

The objective constraint, like the ergodic capacity of the BB-RSA-based CRN, is analysed under "interference power threshold, number of SUs, SINR and transmission power" by comparing with existing heuristic algorithms as shown in Figure 4. The ergodic capacity seems to be 8.9%, 9.12%, 12.4%, and 11.2% better than the than ALE-TWGO, MLF-AEO, BBA, and RSA, respectively. Hence, it is revealed that maximum ergodic capacity is achieved through the developed BB-RSA-based model.

6.4 *Outage probability analysis*

The developed BB-RSA is used for reducing the outage probability for making efficient transmission in CRN, estimated through Figure 5. From this analysis, the outage probability is observed to be lower when compared to other baseline algorithms, which can be observed in all the iterations.

6.5 *Throughput analysis*

The throughput of the developed BB-RSA-based CRN model has been analysed with various existing algorithms, as shown in Figure 6. The developed BB-RSA utilised for enhancing the throughput performance, which is 11.3%, 15.5%, 12.5%, and 10.5% improved than ALE-TWGO, MLF-AEO, BBA, and RSA, respectively. Therefore, it is revealed that enhanced throughput was achieved through the developed model.

Figure 4 Ergodic capacity analysis on proposed BB-RSA-based optimal channel allocation and power control strategy in CRN regarding, (a) interference power threshold (b) a number of SUs (c) SINR (d) transmission power (see online version for colours)

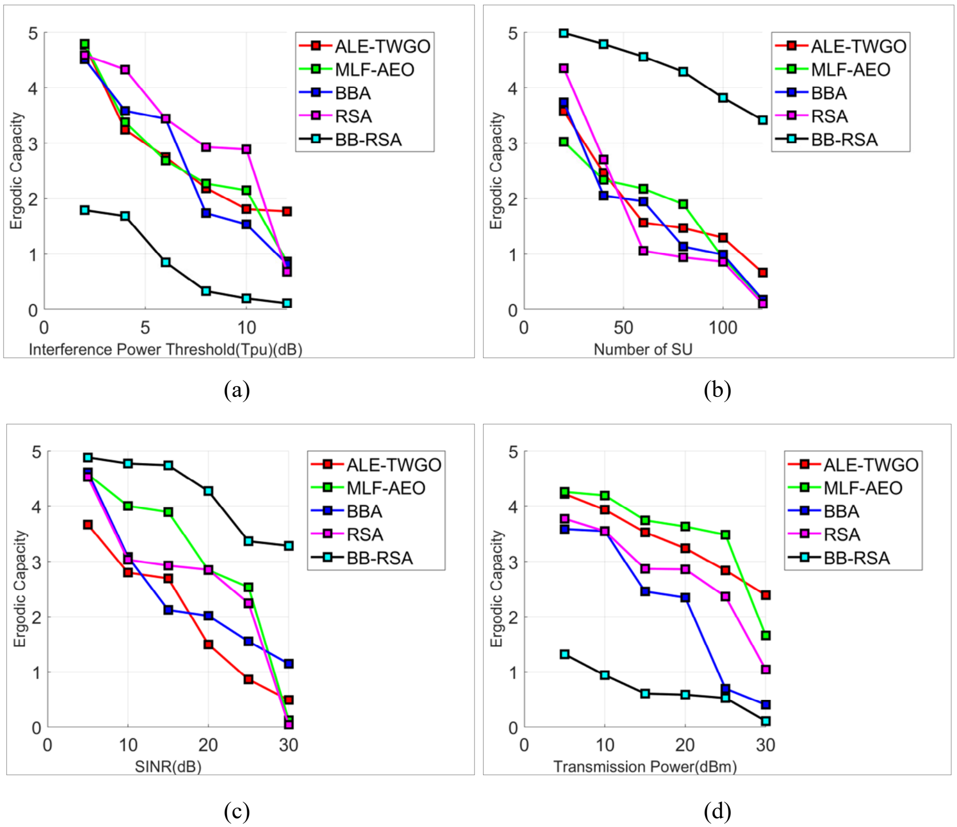


Figure 5 Outage probability analysis on proposed BB-RSA-based optimal channel allocation and power control strategy in CRN concerning, (a) interference power threshold (b) a number of SUs (c) SINR (d) transmission power (see online version for colours)

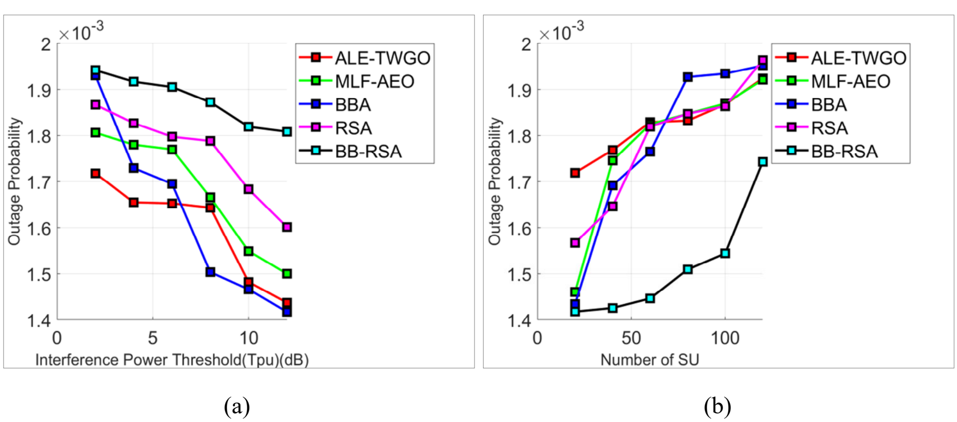
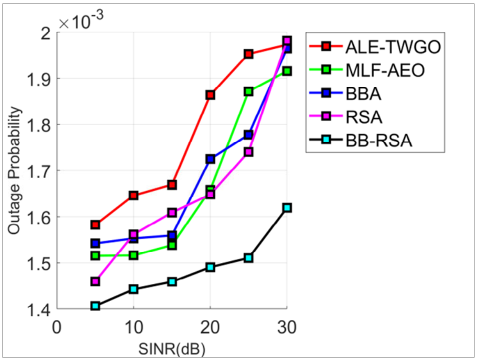
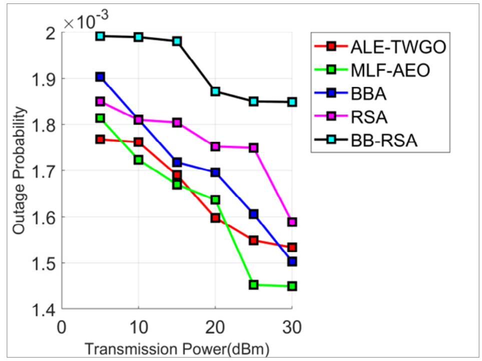


Figure 5 Outage probability analysis on proposed BB-RSA-based optimal channel allocation and power control strategy in CRN concerning, (a) interference power threshold (b) a number of SUs (c) SINR (d) transmission power (continued) (see online version for colours)

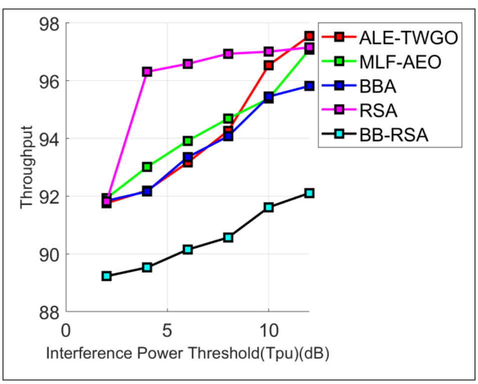


(c)

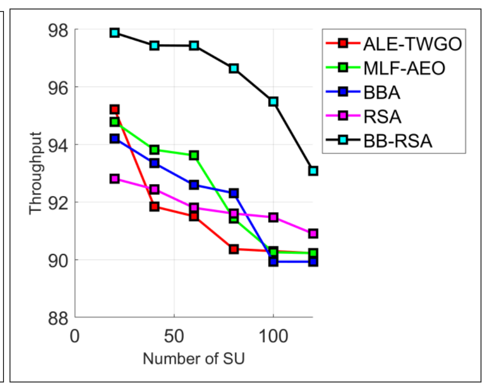


(d)

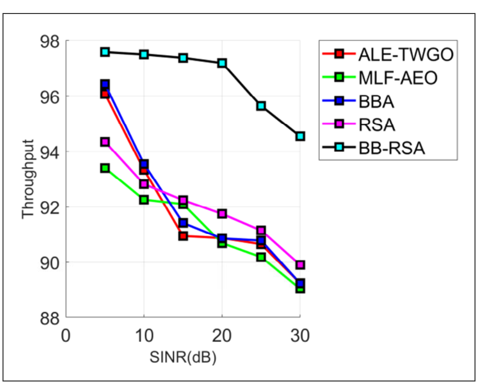
Figure 6 Throughput analysis on proposed BB-RSA-based optimal channel allocation and power control strategy in CRN in terms of, (a) interference power threshold (b) a number of SUs (c) SINR (d) transmission power (see online version for colours)



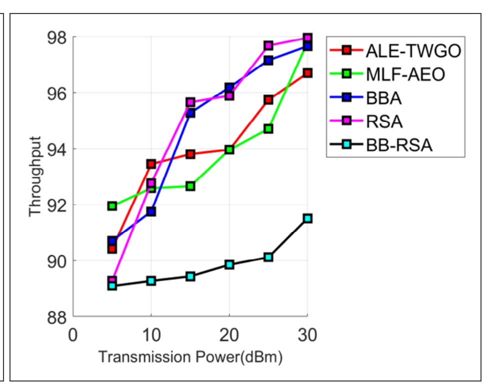
(a)



(b)



(c)



(d)

6.6 Statistical analysis on developed BB-RSA

The statistical measures like best, worst, mean, median, and standard deviation are involved in evaluating the statistical performance of the developed BB-RSA towards optimal channel allocation and power control, as depicted in Table 2. The developed model based on BB-RSA gives 12.5%, 10.9%, 13.2%, and 9.2% improvement over ALE-TWGO, MLF-AEO, BBA, and RSA, respectively. Hence, an efficient optimal solution was obtained for channel allocation and power control in the developed CRN model.

Table 2 Statistical evaluation on developed BB-RSA-based optimal channel allocation and power control in CRN

Algorithms	*Best*	*Worst*	*Mean*	*Median*	*Standard deviation*
ALE-TWGO [27]	7.5206	8.1273	7.55	7.5206	0.12002
MLF-AEO [28]	7.4826	7.7191	7.5577	7.4826	0.085428
BBA [26]	7.5555	7.9866	7.6084	7.6098	0.06766
RSA [29]	7.4893	7.7264	7.5611	7.5354	0.078688
BB-RSA	7.4418	8.182	7.5414	7.4563	0.1619

6.7 Various constraints-based time analysis

The time analysis is conducted for the developed BB-RSA-based optimal channel allocation and power control in CRN to verify with certain analysis constraints like "interference power threshold, number of secondary users, SINR and transmission power", depicted in Table 3. The developed BB-RSA secures 11.4%, 10.9%, 8.9%, and 7.8% better efficiency than ALE-TWGO, MLF-AEO, BBA, and RSA, respectively, when considering the transmission power. Thus, the developed CRN model obtains the optimal solution for solving the power control and channel allocation problem using the developed BB-RSA.

Table 3 Time Estimation on developed BB-RSA-based optimal channel allocation and power control in CRN

Analysis constraints/algorithms	*ALE-TWGO [27]*	*MLF-AEO [28]*	*BBA [26]*	*RSA [29]*	*BB-RSA*
'Transmission power'	0.61235	0.64604	0.59941	0.58845	0.53367
'Inference power threshold'	0.67897	0.76394	0.7506	0.71921	0.66254
'SINR'	0.60457	0.56779	0.57183	0.59437	0.55858
'Number of SU'	0.80514	0.75997	0.83791	0.75633	0.74819

7 Conclusions

This paper has presented a novel optimisation strategy for solving the channel allocation and power control problems on the CRN to enhance transmission performance. The multi-objective constraints were considered as maximising the throughput and ergodic capacity and also minimising the outage probability among the data transmission between

PUs and SUs. This multi-objective function was achieved by utilising the developed BB-RSA by optimising the channel allocation and power control variables to get efficient transmission. The analyses have shown that the developed BB-RSA was 12.5% better than ALE-TWGO, 10.9% improved than MLF-AEO, 13.2% enhanced than BBA, and 9.2% elevated than RSA. Thus, it was confirmed that the developed BB-RSA-based channel allocation and power control strategy had attained better transmission efficiency by enhancing the throughput and ergodic capacity as well as minimum outage probability was also attained. Some limitations of the developed optimal channel allocation and power control in CRN are shown below. The multivariate fraction summation issue was still a challenging problem in optimal channel allocation and power control in the CRN network. Moreover, it requires a more number of neighbouring servers and remote clouds to coordinate the task in load balancing since it suffers from heavy signalling in channel allocation. In practical implications, the CRN helps to resolve the computational problems in the MINLP model when they are implemented in large-scale networks. Here, the controlling of power in CRN helps to improve the system's robustness. In the future, the non-orthogonal multiple access (NOMA) based mobile edge computing system in channel allocation will be evaluated for decreasing the time interval between the users and base stations.

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