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Throughput Optimization in Multi-user Cognitive Radio Network using Swarm Intelligence Techniques

ASHIM JYOTI GOGOI*, NAUSHAD MANZOOR LASKAR, CH. LISON SINGH, KRISHNA LAL BAISHNAB AND KOUSHIK GUHA
Department of Electronics and Communication Engineering
National Institute of Technology
Silchar, 788010 India
E-mail: ashimgogoi@ieee.org; naushad@ece.nits.ac.in; 14-3-04-106@students.nits.ac.in; klb@ece.nits.ac.in; koushik@ece.nits.ac.in*

Throughput efficiency holds great importance in the present scenario of the cognitive radio system. In this paper, optimization of throughput in multi-user single relay cognitive radio system has been performed. In a multi-user cognitive radio network, collisions occur between data packets of multiple secondary users, which cause a reduction in the throughput of the network to a great extent. In this paper, a new analytical model for throughput of the multi-user cognitive radio network in terms of the probability of collision has been presented. The model is convenient for the formulation of the optimization problem in such a way that an optimal value of throughput can be achieved by keeping the probability of collision below the allowable limit. This leads to an enhancement in throughput as well as maintains system reliability in the cognitive radio network. Optimal power allocation scheme is used to allocate power among secondary users which makes the system energy efficient. The optimization of the throughput of the system is done using swarm intelligence-based optimization techniques like Particle Swarm Optimization (PSO), Human behavior based Particle Swarm Optimization (HPSO), Particle Swarm Optimization with Aging Leader and Challengers (ALCPSO) and Whale Optimization Algorithm (WOA). Simulation results illustrate that the system optimized with WOA have better throughput than that of the aforementioned optimization algorithms. Moreover, a comparative analysis of the achievable throughput in the multi-user cognitive radio system with the proposed scheme and that with the equal power allocation scheme is presented. The analysis reveals that the proposed scheme makes the system more efficient in terms of throughput than equal power allocation scheme.

Keywords: multi-user cognitive radio network, probability of detection, probability of false alarm, Poisson distribution, throughput, particle swarm optimization (PSO)

1. INTRODUCTION

In the present times, the numbers of wireless devices are increasing tremendously, which causes scarcity in radio frequency spectrum. In a survey conducted by Federal Communication Commission (FCC), it is revealed that under the static spectrum allocation, only 5% to 15% of spectrum is utilized generally [1]. To solve the spectrum under-utilization problem, dynamic spectrum assignment (DSA) schemes are proposed. DSA can be done by implementing policy based intelligent networks known as cognitive radios [2]. These types of networks have been drawing a great attention in the field of wireless communications, because of their great spectrum efficiency. In such networks, an unlicensed or secondary user (SU) can access the spectrum, if it is unoccupied by the

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licensed or primary user (PU). The cognitive radio network performs spectrum sensing operation to sense the radio environment in order to find the available spectrum band that can be accessed by SUs. Different types of spectrum sensing techniques have been proposed so far. Some of these techniques are Energy detection based sensing, Cyclostationarity-based sensing, Radio identification-based sensing, Waveform-based sensing *etc*. [3].

Efficient utilization of spectrum is of utmost importance which desires high throughput of the cognitive radio network. Design of throughput efficient cognitive radio system maintaining the reliability of the network is an emerging area of research. Liang *et al.* [4] derived a theoretical formula for achievable throughput of SU and it was illustrated that there exists an optimal spectrum sensing time which provides the highest throughput for the cognitive radio network. A novel cognitive radio system was proposed in [5], which performs spectrum sensing and data transmission at the same time and also provides better sensing-throughput tradeoff. Rashid *et al.* [6] proposed a particle swarm optimization (PSO)-based scheme to address the tradeoff between sensing time and throughput of SUs. Using that approach a significant improvement in throughput is achieved compared with non-optimal sensing scheme.

In relay-based wireless networks, relays receive signals from the source node and retransmit the amplified version of the received signals to the destination node. Relays are utilized in the cognitive radio network to enhance the spectrum sensing reliability and to increase the throughput of SUs [7-12]. Tabatabaee *et al.* [8] proposed an infrastructure based cooperative spectrum sensing scheme is presented which illustrated that each of the SUs forwards the individual sensing results to a fusion center (FC) through an error-free common control channel. The FC combines the individual sensing results of SUs to determine presence or absence of PU in the sensed channel. If FC finds the absence of primary users in the sensed channel, then it allows the secondary users to transmit in the channel. In [9], an energy-efficient cooperative spectrum sensing in a relay-based cognitive radio network using equal power allocation scheme was presented. Huang *et al.* [10] proposed an optimal power allocation strategy for maximization of the throughput of SUs under both sensing reliability and power constraints in cognitive relay networks. Song *et al.* [11] designed a cognitive relay system that jointly optimizes sensing time and signal-to-noise to maximize throughput and energy efficiency of the system. Minimizations of energy consumption in data transmission process of multi-relay cognitive radio network were done in [12]. In [13], the contention probability in multi-user cognitive radio network was minimized to obtain better delay performance in data transmission process. In [14], the tradeoff between sensing performance and data transmission energy of amplify-and-forward relay scheme considering both the case of fixed and variable amplifying gain was analyzed. The analysis reveals that there exists an optimal amplification gain to strike the best tradeoff between sensing performance and energy consumption. In [15], the problems of route lifetime maximization and interference to primary user minimization were jointly investigated in outage constrained cognitive radio networks. Optimization of throughput in cognitive radio network under interference temperature constraints was done in [16]. In [17], the optimization of throughput in energy harvesting (EH) relay based interweave/underlay cognitive radio network is done. Wu *et al.* [18] illustrated the impact of video size on a practical mobile Device-to-Device video distribution and proposed a general global estimation of the video distribution based on the limited and local observation. In [18], it was considered that for Device-to-Device communication, there was a licensed spectrum. But, in our paper, it is considered that there is no licensed spectrum is assigned for communication for Device-to-Device communication in the cognitive radio network. Rather, the network utilizes the spectrum which is not utilized by primary network. Also in [18], the system performance was not demonstrated in terms of throughput, which is done in our paper. Zhou [19] proposed a social-aware rate based content sharing mode selection scheme for Device-to-Device content sharing scenarios. In [19], the spectrum was shared among multiple devices maintaining link quality of the network. But, in our proposed work, the licensed spectrum is not shared among SUs, the SUs opportunistically access the spectrum unused by PUs.

In a cognitive radio network, collisions may occur between data packets of SUs, which cause a reduction in the throughput of SUs. In the aforementioned papers, analyses of the throughput in cognitive radio network considering the probability of collision have not been done. In the relay-based cognitive radio networks, a high value of amplifying gain causes interference at the primary network and a low value of the gain causes an outage at the secondary destination. So, the optimal range of amplifying gain should be determined, so that both interference and outage probability can be kept below a predefined threshold value, which is not done in any of the previously mentioned works. The contributions of the paper are given as follows.

Firstly, a new analytical model of throughput of the multi-user cognitive radio network in terms of probability of collision between packets of multiple SUs has been proposed. The model is convenient to optimize the throughput in such a way that the probability of collision between packets of SUs can be kept below a predefined threshold.

Secondly, to keep the undesirable effects of outage probability and interference effects below allowable limits, an optimal range of amplifying gain of the relay has been determined.

Thirdly, the throughput optimization of the proposed system is done using swarm intelligence-based optimization algorithms like PSO [20, 21], HPSO [22], ALCPSO [23] and WOA [24] maintaining the reliability of the system.

The reasons to choose the swarm intelligence-based optimization algorithms are that these techniques have been found to be computationally efficient in solving optimization problems in terms of good computational time complexity, fast convergence and are derivative free [20-26]. The results show that the proposed scheme makes the cognitive radio system more efficient in terms of throughput than the equal power allocation scheme [9, 17]. Besides, the proposed scheme enables the multi-user cognitive radio network to cause less interference effect to the primary network in comparison with the equal power allocation scheme. The remainder of the paper is organized as follows. In Section 2 the system model is presented, while optimal limits for amplifying gain of AF relay is presented in Section 3. Collisions between data packets of multiple users are discussed in Section 4. The problem formulation and description of optimization process are presented in Sections 5 and 6 respectively. Results and discussions are presented in Section 7 and finally, conclusions are drawn in Section 8.

2. SYSTEM MODEL

As shown in Fig. 1, the proposed system model consists of an infrastructure based multi-user single relay cognitive radio network and a primary network. The cognitive radio network consists of m numbers of secondary users (SUs), an amplify-and-forward (AF) relay, a fusion center (FC) and a secondary base station (SBS). The primary network consists of a primary user (PU) and a primary base station (PBS). In the primary network, the PU sends data to PBS. The SUs are allowed to send data only when the PU doesn't send data through the channel. The SUs transmit data to the base station through the AF relay. The AF relay is used here mainly so as to amplify the signals of the SUs even though they lie far away from the SBS.

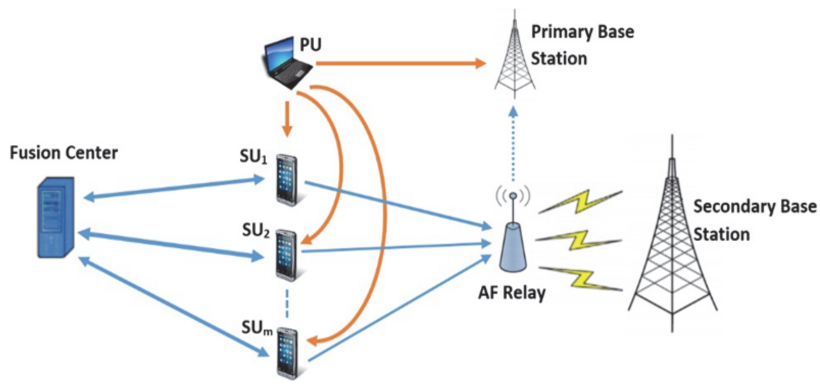

Fig. 1. System model.

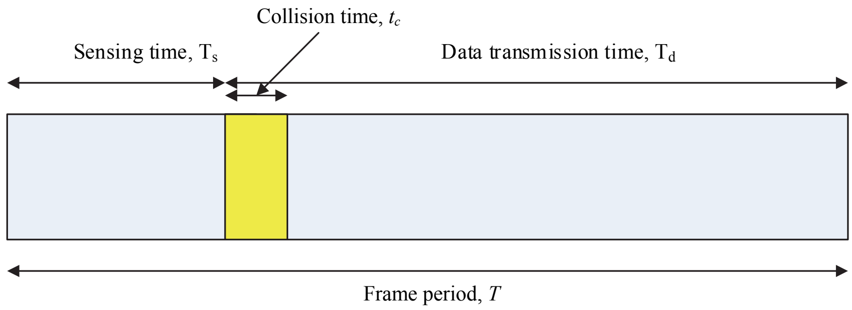

Fig. 2. Time frame structure of cognitive radio network.

The cognitive radio network works on a frame-by-frame basis, *i.e.*, a channel is allocated to SUs for the time frame of duration T. The time frame has been split into two slots for sensing and data transmission respectively as shown in Fig. 2. During sensing time T_s, the channel is sensed by SUs to monitor the existence of PU. In the sensing process, if there is no primary user found in the sensed channel then SUs will use the remaining duration of the time frame *i.e.*, $(T - T_s)$ for the purpose of data transmission. The discussion about the collision time of the time frame is done in section 4. During data transmission time, the SUs send signals to the AF relay. The relay forwards the amplified version of the received signals to the SBS. In the transmission process, there may be interference to the PBS from the AF relay, which is denoted by the dotted line in Fig. 2. After receiving the signals of different SUs, the SBS forwards the signals of different users to their corresponding destinations. In this paper, optimization of throughput of

SUs at the SBS is concerned. For sensing purpose, the energy detection based cooperative spectrum sensing scheme [8] is used. In this scheme, each of the SUs forwards the individual sensing results to the FC through an error-free common control channel. The FC combines the individual sensing results of SUs using OR fusion rule to determine presence or absence of PU in the sensed channel. If FC finds the absence of a signal of the PU in the sensed channel, then SUs are allowed to transmit through the channel.

In the sensing process, the probability of detection (P_{d_i}) and the probability of false alarm (P_{f_i}) is determined by different SUs in the network. P_{d_i} is the probability that ith SU correctly decides the existence of primary user signal and P_{f_i} is the probability that it wrongly decides the presence of primary user signal although it is absent in the sensed channel. These probabilities are given by [4]

$$P_{f_i} = Q\left(\left(\frac{\varepsilon}{P_n} - 1\right)\sqrt{N}\right), \tag{1}$$

$$P_{d_i} = Q\left(\left(\frac{\varepsilon}{P_n} - 1 - \gamma_i\right)\sqrt{\frac{N}{2\gamma_i + 1}}\right). \tag{2}$$

Here, γ_i represents the received the signal-to-noise ratio of PU at the ith SU during data transmission time and N number of sensing samples. The individual detection probabilities of SUs are sent to the FC. The cooperate probability of false alarm (P_f) and the cooperate probability of detection (P_d) of the network determined at FC by combining the individual sensing results of SUs using OR fusion rule. The expressions of P_d and P_f are given by [4]

$$P_f = 1 - \prod_{i=1}^{m}\left(1 - P_{f_i}\right), \tag{3}$$

$$P_d = 1 - \prod_{i=1}^{m}\left(1 - P_{d_i}\right). \tag{4}$$

Here, m is the number of SUs in the system. In the multi-user cognitive radio system, the different user access a channel in time division multiple access (TDMA) manner. The received signal-to-noise ratio (γ_r) of SUs at SBS during data transmission time is given as

$$\gamma_r = \frac{\sum_{i=1}^{m} \alpha G_{rb} G_{s_i r} P_{s_i}}{\sum_{i=1}^{m} \alpha G_{rb} P_n + P_n}. \tag{5}$$

Here, α is the amplification gain of the relay, P_n is noise variance, P_{s_i} is the transmission power of the ith SU in the network, G_{rb} is channel gain from AF relay to the SBS and $G_{s_i r}$ is the channel gain from ith SUs to the AF relay. The average transmission power of the AF relay is given as

$$\begin{aligned}\overline{P}_t &= P(H_1)\alpha\left(\sum_{i=1}^{m} G_{s_i r}P_{s_i} + G_{pr}P_p + P_n\right) + \left(1-P(H_1)\right)\alpha\left(\sum_{i=1}^{m} G_{s_i r}P_{s_i} + P_n\right)\\ &= \alpha\left(\sum_{i=1}^{m} G_{s_i r}P_{s_i} + P(H_1)G_{pr}P_p + P_n\right).\end{aligned} \tag{6}$$

Here, P_p is transmission power of the PU, G_{pr} is the channel gain from the PU to the relay and $P(H_1)$ is the probability of the presence of the signals of the PU in the sensed channel. In this work, optimal power allocation strategy [10] is used so that the system can be energy efficient. If $P_{\max}$ is the total transmission power budget of the cognitive radio network, then the power equality constraint can be written as

$$\sum_{i=1}^{m} P_{s_i} + \overline{P}_t \le P_{\max}. \tag{7}$$

It is considered that the network utilized the maximum power budget and the transmitted power of all SUs are same, *i.e.*, $P_{s_1} = P_{s_2} = \ldots = P_{s_i} = P_s$. So, from Eqs. (6) and (7)

$$P_s = \frac{P_{\max} - P(H_1)\alpha G_{pr}P_p}{m + \alpha\sum_{i=1}^{m} G_{s_i r}}. \tag{8}$$

From Eqs. (5) and (8) the received signal-to-noise ratio at SBS can be given as

$$\gamma_r = \frac{\alpha\sum_{i=1}^{m} G_{s_i r}G_{rb}\left[P_{\max} - P(H_1)\alpha G_{pr}P_p\right]}{\left(\alpha\sum_{i=1}^{m} G_{rb}P_n + P_n\right)\left(m + \alpha\sum_{i=1}^{m} G_{s_i r}\right)}. \tag{9}$$

If γ_r is the received signal-to-noise ratio, then the throughput at the SBS of the cognitive radio system is given as [6]

$$R = P\left(H_0\right)\left(1 - P_f\right)\frac{T_d}{T}\log(1+\gamma_r). \tag{10}$$

Here, $P(H_1)$ is the probability of the absence of the signals of the PU in the sensed channel. From Eqs. (9) and (10), the throughput at the SBS becomes

$$R = P\left(H_0\right)\left(1 - P_f\right)\frac{T_d}{T}\log_2\left(1 + \frac{\alpha\sum_{i=1}^{m} G_{s_i r}G_{rb}\left[P_{\max} - P(H_1)\alpha G_{pr}P_p\right]}{\left(\alpha\sum_{i=1}^{m} G_{rb}P_n + P_n\right)\left(m + \alpha\sum_{i=1}^{m} G_{s_i r}\right)}\right). \tag{11}$$

3. OPTIMAL LIMITS FOR AMPLIFYING GAIN OF THE RELAY

In the cognitive radio network, an AF relay is used to make the system efficient in terms of throughput. The value of amplifying gain of the relay should be chosen carefully so that the system doesn't cause interference to the primary network and at the same time, a good value of throughput can be achieved. In this section, the optimal limits for amplifying gain of the AF relay are investigated. For this, minimization of the two undesirable effects in the network *i.e.*, interference to PBS and outage probability at SBS are considered.

3.1 Inference to PBS

As mentioned earlier, during the transmission process of the cognitive radio network there may be interference to the PBS from the relay. The interference effect should be minimized to make the system more efficient. In Fig. 1, the interference link from the AF relay to PBS is signified by a dotted line. The interference power is expressed as

$$I = P(H_1)(1-P_d)\alpha\left[\sum_{i=1}^{m} G_{s_i r}P_s + G_{pr}P_p + P_n\right]G_{rpb}. \tag{12}$$

Here, G_{rpb} is the channel gain from the relay to the PBS. To maintain efficiency of the cognitive radio network, the interference power to the PBS should be below the predefined threshold Ith, *i.e.*

$$\begin{aligned} &P(H_1)(1-P_d)\alpha\left[\sum_{i=1}^{m} G_{s_i r}P_s + G_{pr}P_p + P_n\right]G_{rpb} \le I_{th}, \\ &\text{or,} \alpha \le \frac{I_{th}}{P(H_1)(1-P_d)\left[\sum_{i=1}^{m} G_{s_i r}P_s + G_{pr}P_p + P_n\right]G_{rpb}} = \alpha_{\max}. \end{aligned} \tag{13}$$

In Eq. (13), $\alpha_{\max}$ represents the upper limit for the amplifying gain of the relay. Therefore, to keep the interference power to the PBS below a predefined threshold, the value of amplifying gain should be less than or equal to $\alpha_{\max}$, *i.e.*, $\alpha \le \alpha_{\max}$.

3.2 Outage Probability

In the cognitive radio network, an outage occurs when the signal-to-noise ratio at destination node fails to achieve a value greater than or equal to a predefined threshold [14]. The outage probability at SBS is given as

$$P_{out} = \Pr(\gamma_r \le \gamma_{\text{th}}) = 1 - \Pr(\gamma_r \ge \gamma_{\text{th}}). \tag{14}$$

In the cognitive radio network, the received instantaneous a signal-to-noise ratio is exponentially distributed with a probability distribution function $f_{\gamma_r}(\gamma)$. It is expressed as

$$f_{\gamma_r}(\gamma) = \frac{1}{\gamma_r}\exp\left(\frac{\gamma}{\gamma_r}\right). \tag{15}$$

From Eqs. (14) and (15)

$$P_{out} = 1 - \int_{\gamma_{th}}^{\infty} \frac{1}{\gamma_r} \exp\left(\frac{\gamma}{\gamma_r}\right) = 1 - \exp\left(\frac{-\gamma_{th}}{\gamma_r}\right) = 1 - \exp\left(\frac{-\gamma_{th}\alpha\sum_{i=1}^{m} G_{rb}P_n + P_n}{\alpha\sum_{i=1}^{m} G_{rb}G_{s_ir}P_s}\right). \tag{16}$$

For reliable transmission in the cognitive radio network, the outage probability should be below the predefined threshold $\overline{P}_{out}$ *i.e.*,

$$1 - \exp\left(\frac{-\gamma_{th}\alpha\sum_{i=1}^{m} G_{rb}P_n + P_n}{\alpha\sum_{i=1}^{m} G_{rb}G_{s_ir}P_s}\right) \le \overline{P_{out}} \text{ or, } \alpha \ge \frac{P_n}{\ln\left(1-\overline{P_{out}}\right)^{-1}\sum_{i=1}^{m} G_{rb}G_{s_ir}P_s - \gamma_{th}\sum_{i=1}^{m} G_{rb}P_n} = \alpha_{\min} \tag{17}$$

In Eq. (17), $\alpha_{\min}$ represents the lower limit for the amplifying gain of the AF relay. So, to keep the outage probability below $\overline{P}_{out}$, the value of amplification gain should be greater than or equal to $\alpha_{\min}$, *i.e.*, $\alpha \ge \alpha_{\min}$.

4. COLLISION BETWEEN DATA PACKETS OF MULTIPLE USERS

In the multi-user cognitive radio system, if it is found in the sensing process that a channel is unused by PUs then multiple SUs may try to access the channel within a small duration of time. In such scenario, the collisions occur between data packets of SUs. A scenario of collision in the multi-user cognitive radio network is illustrated in Fig. 3. As shown in Fig. 3, there are k channels in the system, out of which channel 1 is found to be unoccupied by PU. There is a collision between data packets of SUs when two SUs *i.e.*, SU_1 and SU_2 start transmission in channel 1 within the small duration of time t_c. In this way, there may be collisions between packets of SUs in the multi-user cognitive radio network. The small duration of time (t_c) is referred as collision time in this paper. t_c is signified in the time frame structure given in Fig. 2. The collision between data packets of SUs causes a decrease in throughput of the cognitive radio network. The reasons are: firstly, collisions between data packets of SUs cause loss of data packets. Secondly, the collisions resist the data packets to reach the destination node, which decreases the data rate in the cognitive radio network. So, for efficient transmission, the probability of collision should be minimized. Different users send different numbers of data packets during data transmission time. For computational simplicity, it is considered that each of the m numbers of SUs transmits one data packet during data transmission time of a time frame. The data transmission process follows Poisson distribution [27]. So, the data transmission rate is given by

$$\lambda = \frac{m}{T_d}. \tag{18}$$

Following the Poisson arrival process, the probability that j numbers of transmissions of SUs occurred in the interval $[0, t_c]$ is given as

$$p(j;t_c) = e^{-\lambda t_c}\frac{[\lambda t_c]^j}{j!} = e^{-m\frac{t_c}{T_d}}\left[m\frac{t_c}{T_d}\right]^j / j! \tag{19}$$

Here, j = 0, 1, 2, …, ∞. Considering the fact that there is a collision during data transmission time if there is at least two transmissions occur in the time interval $[0, t_c]$, the probability of collision between packets of SUs is given as

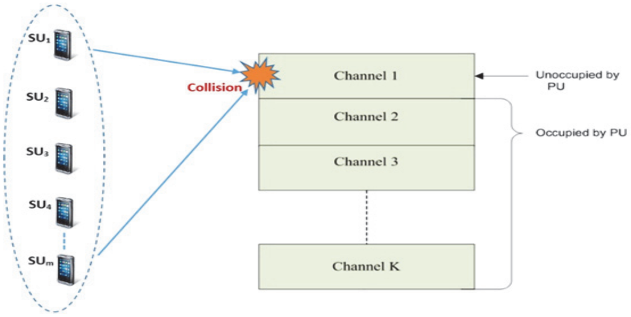

Fig. 3. Collision between data packets of SUs.

$$P_c = \sum_{j=2}^{\infty} P(j;\ t_c) = 1 - P(0;\ t_c) - P(1;\ t_c) = 1 - e^{\frac{-mt_c}{T_d}} - \frac{mt_c}{T_d} e^{\frac{-mt_c}{T_d}}$$
$$\text{or, } P_c = 1 - e^{\frac{-mt_c}{T_d}} \left(1 + \frac{mt_c}{T_d}\right). \tag{20}$$

Expanding the exponential term in Eq. (20)

$$P_c = 1 - \left(1 - \frac{mt_c}{T_d} + \frac{1}{2}\left(\frac{mt_c}{T_d}\right)^2 + ...\right)\left(1 + \frac{mt_c}{T_d}\right). \tag{21}$$

In Eq. (21), the terms of order 3 and more, have very low values. Therefore, neglecting these terms and simplifying Eq. (21), the probability of collision becomes

$$P_c = \frac{1}{2}\left(\frac{mt_c}{T_d}\right)^2. \tag{22}$$

From Eq. (22), the data transmission time in terms of the probability of collision is given by

$$T_d = \frac{mt_c}{\sqrt{2P_c}}. \tag{23}$$

As shown in Fig. 2, the total duration of time frame allocated to the SUs of the multi-user cognitive radio system for sensing and data transmission process is given by

$$T = T_s + T_d. \tag{24}$$

From Eqs. (23) and (24)

$$T = T_s + \frac{mt_c}{\sqrt{2P_c}}. \tag{25}$$

From Eqs. (11) and (25), the throughput expression can be written as

$$R = P(H_0)(1-P_f)\frac{mt_c}{\left(\sqrt{2P_c}T_s + mt_c\right)}\log_2\left(1+\frac{\alpha\sum_{i=1}^{m}G_{s_ir}G_{rb}\left[P_{\max}-P(\mathrm{H}_1)\alpha G_{pr}P_p\right]}{\left(\alpha\sum_{i=1}^{m}G_{rb}P_n+P_n\right)\left(m+\alpha\sum_{i=1}^{m}G_{s_ir}\right)}\right). \quad (26)$$

5. PROBLEM FORMULATION

In a multi-user cognitive radio network, the collision between samples of SUs causes the decrease in throughput of the system. The main aim of this paper is to optimize the throughput of the multi-user cognitive radio network such that the value of probability of collision between the data packets of SUs should be lower than the predefined threshold. In the optimization process, an optimal range of amplifying gain of the relay is maintained to keep undesirable effects like interference to the PBS and outage probability below allowable limits. The optimization problem is formulated as

$$\max R = P(H_0)(1-P_f)\frac{mt_c}{\left(\sqrt{2P_c}T_s + mt_c\right)}\log_2\left(1+\frac{\alpha\sum_{i=1}^{m}G_{s_ir}G_{rb}\left[P_{\max}-P(H_1)\alpha G_{pr}P_p\right]}{\left(\alpha\sum_{i=1}^{m}G_{rb}P_n+P_n\right)\left(m+\alpha\sum_{i=1}^{m}G_{s_ir}\right)}\right)$$

$$s.t.\begin{cases} P_f \le \overline{P_f}, P_c \le \overline{P_c} \\ \dfrac{P_n}{\ln\left(1-\overline{P_{out}}\right)^{-1}\sum_{i=1}^{m}G_{rb}G_{s_ir}P_s-\gamma_{th}\sum_{i=1}^{m}G_{rb}P_n} \le \alpha \le \dfrac{I_{th}}{P(H_1)(1-P_d)\left[\sum_{i=1}^{m}G_{s_ir}P_s+G_{pr}P_p+P_n\right]G_{rpb}} \end{cases}. \quad (27)$$

Here, R is the throughput to be optimized, $\bar{P_f}$ is the threshold value of probability of false alarm and $\bar{P_c}$ is the threshold value of probability of collision between samples of SUs. The upper and lower limits of amplifying gain of CR are obtained from Eqs. (13) and (17) respectively.

6. OPTIMIZATION PROCESS

Swarm intelligence-based optimization algorithms such as PSO [20, 21], HPSO [22], ALCPSO [23] and WOA [24] are used to optimize the throughput of the multi-user cognitive radio network satisfying the constraints given in Eq. (27).

In this paper, the problem statement involves maximizing the throughput for multi-user cognitive radio network such that the values of system parameters lie within acceptable ranges. For this, a new analytical expression for throughput considering the collision probability among the data packets of SUs is derived and the optimization problem is formulated as given in Eq. (27). The swarm intelligence-based algorithms

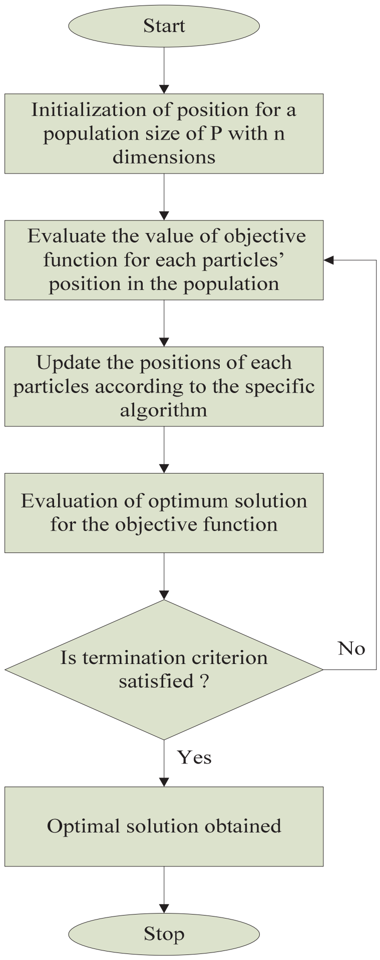

Fig. 4. Flowchart of the optimization process.

initialize population for a population size of P with n dimensions to solve the optimization problem. The particles in the population signify the tentative solutions to the optimization problem. Each of the algorithms has its own approach towards finding the best possible solution for the optimization problem. However, a common working approach is modeled using which the algorithms are applied in solving the objective function for the considered problem statement. The flowchart of the optimization process using the optimization algorithms in this work is shown in Fig. 4. In the optimization process, the values of the constraints are set as given in section 7. Then, the position update processes for each algorithm is carried out several times until the best solution for the respective algorithm satisfying all the constraints of the optimization problem is achieved. The time complexity [28] of swarm intelligence-based algorithms is $O(n \times P + P \times cof)$, where n is the dimension of the problem and P is the population size and cof is the cost of the objective function. The term cof varies according to the optimization process of the algorithms. In the analysis of the complexity, $n \times P$ signifies the computation of solutions for a population of size P with n dimensions. $P \times \log_2 P$ signifies the sorting of best solution among P numbers of solutions. The computational time complexity of the algorithms to solve the optimization problem is given in Table 1. From the Table 1, it is noticed that PSO is better in terms of computational time complexity than the other algorithms.

Table 1. Computational time complexity of the algorithms.

Algorithm	Complexity
PSO	$O(n \times P + P \times (2 + \log_2 P))$
HPSO	$O(n \times P + P \times (2 + 2 + \log_2 P))$
ALCPSO	$O(n \times P + P \times (2 + 8 \times n + \log_2 P))$
WOA	$O(n \times P + P \times (1 + 2 \times n + \log_2 P))$

7. RESULTS AND DISCUSSIONS

This section presents the performance of the proposed scheme in the multi-user cognitive radio system in terms of throughput and other system parameters. The specifications for each of the parameters in the optimization problem are set in such a way that reliability of the cognitive radio system can be improved as compared to non-optimized systems. To maintain the standards of Federal Communications Commission (FCC), the maximum acceptable probability of false alarm is set as 10% and the minimum probability of detection is set as 90% [6]. The probability of PUs to be inactive is taken as 80%. To increase the throughput of SUs, the probability of collision should be kept below a predefined threshold. The threshold value of the probability is taken as 8%. As the amplifying gain of the AF relay increases, the amplitude of signals of SUs also increases, which in turn causes interference to the primary network. By keeping the amplifying gain below the upper limit ($\alpha_{\max}$), the interference to the PBS can be kept below the predefined threshold. This has been illustrated in section 3.1. Again, lower value of amplifying gain of the AF relay leads to the occurrence of an outage at SBS. So, by keeping the value of the amplifying gain above the lower limit ($\alpha_{\min}$), the occurrence of the outage at SBS can be avoided, which have been illustrated in section 3.2. Therefore the upper and lower limits of the amplifying gain of the AF relay are set based on Eqs. (13) and (17) respectively, which helps to keep outage probability and interference effects below their predefined threshold values.

The values of some of the parameters considered for the optimization process are given in Table 2. For simulations, a specific case of channel conditions has been considered in which $G_{s_i r} = G_{rb} = -5dB$ and $G_{rpb} = -20dB$. The maximum transmission power budget is taken as $P_{\max} = 0.5dBW$. The numbers of SUs in the cognitive radio system is considered as 14. The average transmission power of each of the SUs and the PU is taken as 0 dBW.

Table 2. List of parameters for optimization.

Parameters	$\bar{P}_c$	$\bar{P}_f$	$\alpha_{\min}$	$\alpha_{\max}$	$\bar{P}_{out}$	I_{th}	γ_{th}
Values	8%	10%	1.05	3.56	10%	-20 dBW	4.77 dB

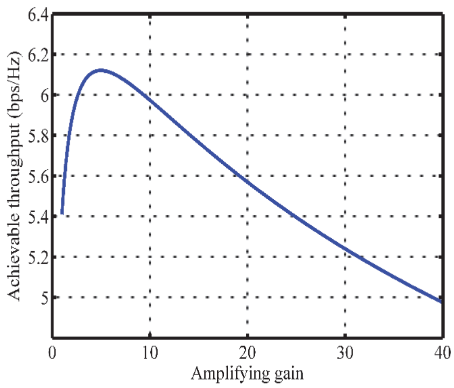

Fig. 5. Average achievable throughput versus amplifying gain of the relay.

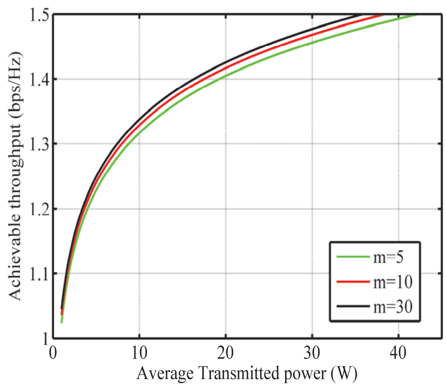

Fig. 6. Average achievable throughput versus transmitted power of SUs.

7.1 Variation of Throughput of the System under Different Parameters

The variation of the average achievable throughput of the multi-user cognitive radio system with the gain of the AF relay is shown in Fig. 5. As observed in Fig. 5, initially the throughput of the system increases with increase in amplifying gain of the relay. After reaching a certain value of gain, the throughput starts to decrease with further increase in the amplifying gain. This is due to the fact that larger value of amplifying gain increases the noise power of the network which in turn causes a decrease in the throughput of the system. Therefore, in the optimization process, an optimal value of the amplifying gain should be found such that the throughput of the system can be increased. The variation of the average achievable throughput of the multi-user cognitive radio system with the average transmitted power of the SUs for m numbers of SUs are presented in Fig. 6. From Fig. 6, it is seen that the average achievable throughput at CR increases with increase in the transmitted power. The throughput also increases with increase in the numbers of SUs. Fig. 7 shows the variation of normalized throughput with respect to the probability of collision between data packets of SUs at different values of probability of false alarm. From Fig. 7, it is observed that as the probability of collision increases, the normalized throughput of the multi-user cognitive radio system decreases. Also, it is seen that the probability of false alarm should be low to obtain a good throughput of the system. So, optimal values of the parameters are required to obtain a good throughput of the cognitive radio network.

7.2 Optimization of the Throughput using Swarm Intelligence-Based Techniques

The objective function defined in Eq. (27), is solved by applying the swarm intelligence-based techniques as mentioned in section 6. Simulations are performed in MATLAB 2013 environment on an i7 processor. The convergence plots of the aforementioned swarm intelligence-based algorithms, *i.e.*, PSO, ALCPSO, HPSO and WOA are shown in Fig. 8. As shown in Fig. 8, the plot for the WOA converges at a higher value of achievable throughput compared to that of the other optimization algorithms. This reveals that though PSO is better in terms of time complexity, the WOA gives a better solution to the optimization problem in terms of achievable throughput than the other aforementioned algorithms. The optimum values of parameters obtained using these three optimization algorithms are given in Table 3. From the table, it can be seen that the system optimized with WOA gives better throughput than the systems optimized with the other three optimization techniques. Also, the probability of collision in the WOA based optimized system is less in comparison to that of the other optimization techniques.

Table 3. Results of optimization process.

Para-meters	PSO based optimum		HPSO based optimum		ALCPSO based optimum		WOA based optimum	
	values of para-meters	through-put (bps/Hz)	values of para-meters	through-put (bps/Hz)	values of para-meters	through-put (bps/Hz)	values of para-meters	through-put (bps/Hz)
P_c	7.50%		5.33%		5.10%		5%	
P_f	4.55%	4.023	2%	4.477	5%	4.553	2%	4.674
α	1.054		2.50		1.234		1.122	

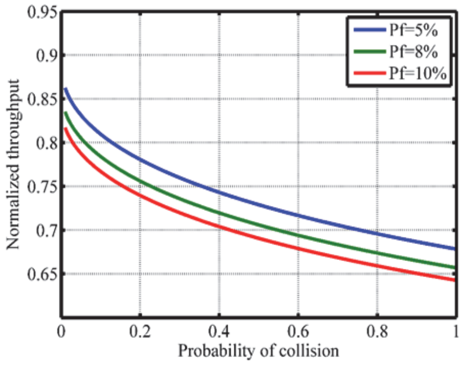

Fig. 7. Normalized throughput of the network versus probability of collision.

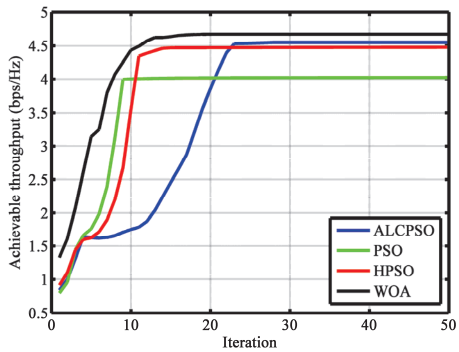

Fig. 8. Convergence plot of the optimization algorithms.

7.3 Performance Comparison

A performance comparison of the proposed WOA based optimal power allocation scheme with equal power allocation scheme [9, 17] in terms of achievable throughput under variation in average transmitted power of the SUs is presented in Fig. 9. Comparative analysis shows that the proposed scheme gives better throughput as compared to the equal power allocation scheme in the multi-user cognitive radio network. Fig. 10 presents a comparison between the proposed WOA based optimal power allocation scheme and equal power allocation scheme, in terms of interference to the PBS under variation in amplifying gain in multi-user cognitive radio network.

From Fig. 10, it can be inferred that for the lower value of amplifying gain equal power allocation performs better than the proposed scheme. But, as the amplifying gain increases, the proposed WOA based scheme demonstrates a lower interference to the PBS as compared to the equal power allocation scheme.

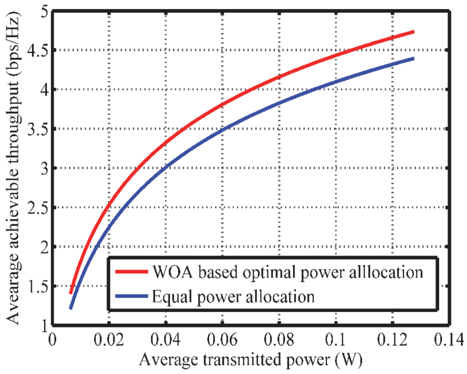

Fig. 9. Average achievable throughput versus transmitted power of SUs.

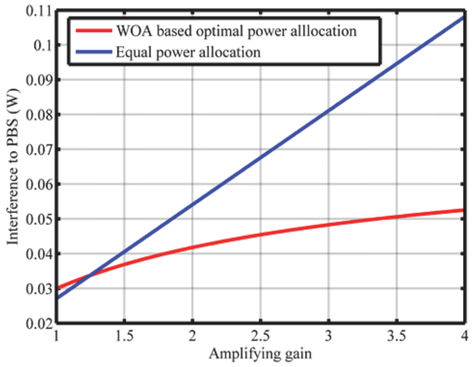

Fig. 10. Interference to PBS versus amplifying gain of the relay.

8. CONCLUSIONS

In this paper, a new analytical model of throughput in the cognitive radio network considering the collisions between data packets of SUs has been proposed. The model is utilized in the optimization of the throughput by minimizing the probability of collision. An optimal range of amplifying gain of AF relay is determined to keep the undesirable effects of outage probability and interference below their predefined threshold values. Swarm intelligence-based optimization algorithms like PSO, ALCPSO, HPSO and WOA are used to solve the optimization problem. From simulation results, it can be seen that the WOA based optimized system is more efficient in terms of throughput and reliability than that of the other aforementioned algorithms. It is illustrated that the WOA based optimal power allocation scheme is more efficient than equal power allocation scheme in terms of throughput. Moreover, results illustrate that the proposed scheme enables the multi-user cognitive radio network to cause less interference to the primary base station in comparison with the equal power allocation scheme.

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Ashim Jyoti Gogoi received his B.E. degree from Gauhati University and M.Tech degree from NERIST, India in 2010 and 2014, respectively. He is currently pursuing Ph.D. in National Institute of Technology Silchar, India. His research interest includes cognitive radio network, image processing, MIMO communications and modern optimization methods.

Naushad Manzoor Laskar received his B.E. degree in from Royal School of Engineering and Technology in 2013. He received M.Tech from National Institute of Technology, Silchar in 2015. His research interest includes analog VLSI circuits for low frequency and biomedical applications, VLSI physical design and modern optimization methods.

Ch. Lison Singh received his B.E. degree from Manipur Institute of Technology and M.Tech degree from SRM University, Chennai, India in 2010 and 2013, respectively. He is currently pursuing Ph.D. in National Institute of Technology Silchar, India. His research interest includes analog IC design, modern optimization technique and wireless communications.

Krishna Lal Baishnab received his B.E. degree from Regional Engineering College (presently NIT Silchar) in 1995, M. Tech degree from IIT Kharagpur in 2004 and Ph.D. degree from NIT Silchar, India in 2014. He is currently working as an Assistant Professor in National Institute of Technology Silchar, India. His research interest includes wireless system, analog VLSI and RF design.

Koushik Guha received his B.Tech. degree in Electronics and Communication Engineering in 2005 from West Bengal University of Technology, India and his M.Tech. degree in 2007 from Burdwan University, West Bengal, India followed by Ph.D. from NIT Silchar in 2015. Currently, he is an Assistant Professor in NIT Silchar since June 15, 2010. His research interest lies in RF MEMS, analog VLSI, and semiconductor device modeling *etc.*