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Trading-Based Dynamic Spectrum Access and Allocation in Cognitive Internet of Things

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ABSTRACT Next-generation mobile communication networks promise the support for vast number of IoT devices with strong demand for spectrum access. The cater for the continuous growth of IoT applications, one of the challenges to mobile communication network providers is to allow dynamic spectrum access to a gigantic number of densely distributed and low-power IoT networks. In this paper, a novel dynamic spectrum access method is proposed based on spectrum trading for distributed IoT devices. The notion of access benefit is introduced which is based on the purchased band number and modulation mode provided to the mobile user. In the proposed solution, IoT users aim achieve optimization of their spectrum access by ensuring that the spectrum price will not exceed the access benefits from the spectrum trading by solving the spectrum optimization function. Due to the complexity of optimization objective function, pattern search algorithm is utilized to complete the final spectrum allocation optimization. Numerical results are also provided to testify the performances of the proposed spectrum optimization method.

INDEX TERMS Internet of Things (IoT), dynamic spectrum access, spectrum allocation, optimization theory.

I. INTRODUCTION

As the critical part of 5G communications, Internet of Things (IoT) has attracting growing research attention from academia to industria in recent years [1]–[3]. With the continued expansion of IoT applications in various areas including industry 4.0, intelligent agriculture, power grid and smart home, related techniques involved in IoT have been advanced rapidly [4]–[6].

In the next-generation wireless communication networks, the density of wireless terminal blows up which will inevitably lead to the shortage of spectrum resource especially in distributed IoT networks. As a result, the extensive application of IoT may be constrained by crowned wireless spectrum [7]–[10]. To solve this problem, dynamic spectrum sharing and access in light of cognitive radio technology have been investigated to enhance the spectrum efficiency of IoT. During the course, IoT terminals choose the most suitably idle channel to occupy wherein all the spectrum information should be collected by the sensing module equipped in IoT terminals. Many research efforts and mathematical methods have been unfolded to reinforce this cognitive radio-based IoT [11]–[17]. In [11], an optimal channel selection strategy was raised to complete spectrum decision in cognitive radio-based IoT by using reinforcement learning algorithms. Wherein, the channel's future states will be evaluated for following spectrum access. In [12], the authors proposed two cooperative spectrum sensing solutions according to heuristic method. The strategies took into account the spectrum sensing assignment and sensing time to control false alarm probability and optimize the overall available throughput in cognitive radio-based IoT. In [13], a cooperative cognitive

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IoT was considered in which IoT terminals exchange their information with each other and provide relay service for licensed users. In the proposed scheme, IoT devices can harvest essential energy from radio signals sent by primary users. In [14], the authors proposed to utilize the technique of dynamic spectrum access to improve the spectrum utilization in IoT. In this proposal, random and dense full duplex secondary users with sensing capabilities in distributed IoT environment was considered to dynamically use the idle spectrum.

Despite many research efforts have been paid to improve spectrum efficiency in IoT, there are still numbers of challenges to be solved especially in case of heterogenous IoT networks [18]–[21]. Many mathematical tools or theories have been applied in dynamic spectrum sharing or cognitive IoT in which various emphases are addressed in underlay or overlay mode [22]–[26]. Market-driven method for dynamic spectrum access in IoT has received extensive focuses as it can increase primary systems' profits and balance secondary users' spectrum demands meanwhile [5], [27]–[29].

In this paper, a novel dynamic spectrum access method is devised for distributed IoT environment with unsufficient authorized spectrum to be used. When massive IoT terminals need to use licensed spectrum and access wireless networks, how to ensure their communication qualities and spectrum supplement is critical. Effectively dynamic spectrum sharing and access are essential to realize the objective. To smooth the distributed dynamic spectrum access, trading-based spectrum optimization strategy is introduced in which distributed secondary users in IoT make a judgement whether their benefits obtained from the spectrum trading can cover their costs. When the actual benefits received by secondary IoT terminals exceed the band fee, they will choose to access the spectrum. Furthermore, a corresponding optimization function with regards to spectrum allocation for the secondary IoT users is raised to ascertain the band number they should purchase. Due to the complexity of optimization problem, pattern search algorithm is adopted to find the optimal solutions. Numerical results are further provided to testify the performances of our proposed method.

The main contribution of this paper is to address a market-driven dynamic spectrum access method in distributed IoT environments. In this overlay spectrum sharing scenario, the secondary IoT users are considered to pay the band fees and access authorized spectrum after estimating whether they can reap more benefits from this trading. Spectrum price, user preference and modulation mode are the key factors in optimizing spectrum usage for secondary IoT terminals. After fixing the problem of spectrum access, the problem of optimal spectrum allocation is investigated in this distributed environments. Optimization theory is used to solve the fitness function of spectrum allocation in this case.

The rest of this paper is organized as follows. The system model for distributed dynamic spectrum access is given in Section II. Then, the market-based spectrum access decision method along with optimal spectrum allocation strategy are presented in Section III. In Section IV, numerical results are provided to evaluate the proposal's performances. Last, this paper is concluded in Section V.

II. SYSTEM MODEL

With the explosive development of IoT applications and services, related technologies and standards grow up rapidly [30]–[33]. As shown in Fig. 1, a clear architecture framework of cognitive IoT is presented. When massive IoT terminals meet traditional wireless networks, a bottleneck is to be addressed that how to find proper and ample spectrum resource for using. In this scenario, dynamic spectrum access has drawn extensive attention.

In this paper, a cognitive IoT is considered wherein numbers of IoT devices locate as shown in Fig. 2. As shown in Fig. 2, IoT users work in distributed mode and need to lease spectrum from authorized systems. It is assumed that the idle spectrum is collected to be leased in centralized mode, and the leased spectrum is divided into different bands of channels to meet various demands. Thus, in this scenario, the primary systems are supposed to lease the spectrum with total band number of $B = B_1 + B_2 + \cdots + B_N$. When a cognitive IoT device purchases part of bands, according to Ref. [34], the spectrum price can be expressed to be

$$P_B = X + Y \sum_{j=1}^{\tau} B_j \tag{1}$$

where X is a cardinal number for spectrum leasing and Y is a fixed coefficient. τ is the band number and there is $\tau \in [1, N]$. When cognitive IoT terminals are allocated a number of channels, they can transmit on the band. The modulation mode is considered that the IoT terminals use is Quadrature Amplitude Modulation (QAM) to enhance communication quality. Thus, in receiver, according to Ref. [35], the BER expression can be given as

$$BER_i = \frac{1}{5} \exp(\frac{3\gamma}{2^{k+1} - 2}) \tag{2}$$

where γ denotes the SINR in receiver. The parameter k denotes the effective communication benefit which is related to capacity. Yet, it is not equal to capacity as shown in (3). To guarantee the QoS of cognitive IoT terminals' communications, the BER in receiver must be less than a give threshold BER_i^{tar}. And, for cognitive terminal i, the effective communication benefit can be expressed by

$$k_i = \log_2(1 + \xi \gamma_i) \tag{3}$$

where $\xi = 1.5/(\ln(0.2/BER_i^{tar}))$ obtained from (2). Then, for IoT user i, its actual benefits from the spectrum dealing is

$$E_i^c = \varepsilon_i B \log_2(1 + 1.5/(\ln(0.2/BER_i^{tar}))\gamma_i) \tag{4}$$

where ε_i is service type parameter. In cases of various transmission service types, the actual benefits through spectrum trading are different for IoT terminals even in same band width. Besides, the urgency degree of user's spectrum

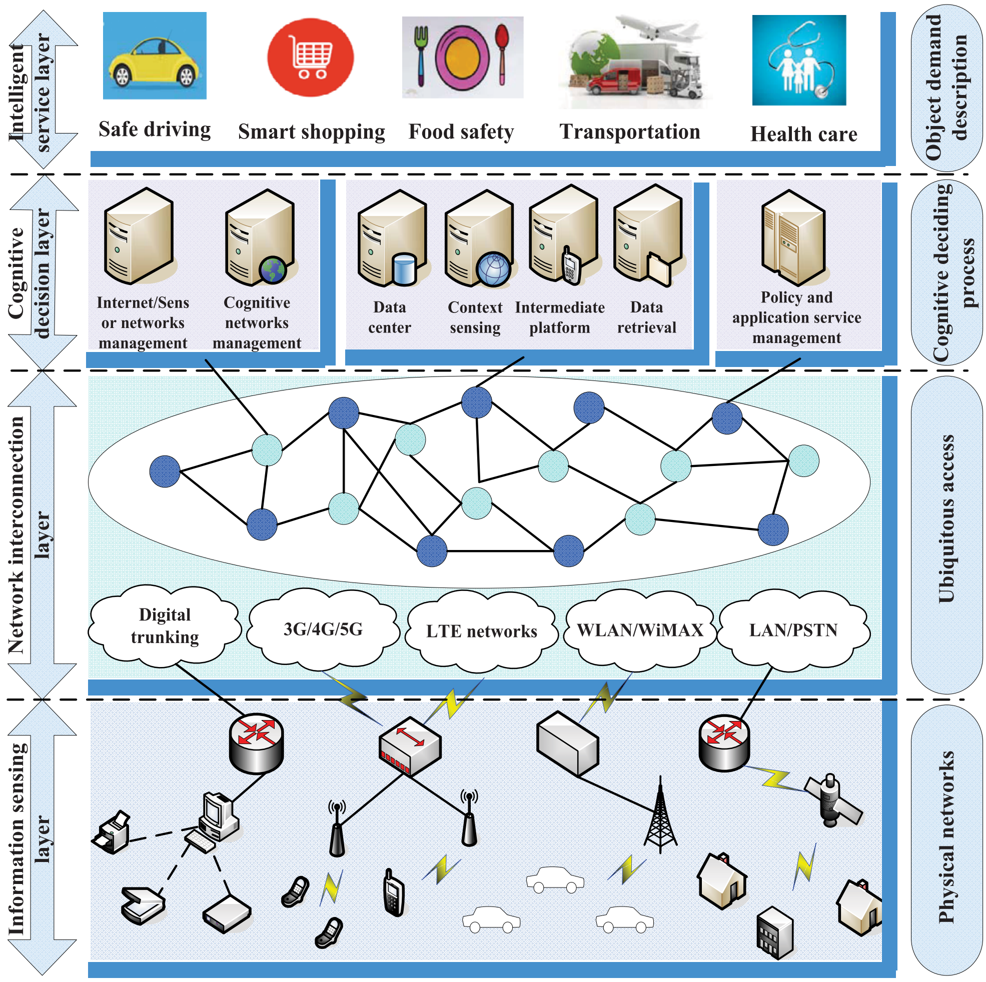

FIGURE 1. Architecture framework of cognitive IoT.

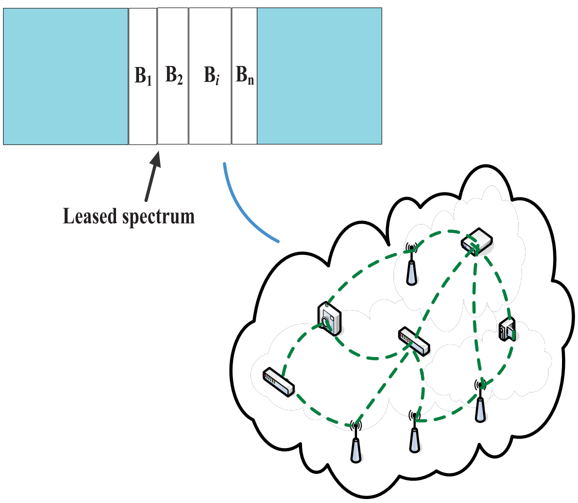

FIGURE 2. Distributed IoT.

demand also matters in most of applications. It can be envisioned that the parameters of ε, Y and k have an apparent impacts on the actual benefits of cognitive IoT users. Higher ε will mean more potential profits for cognitive users through this dynamic spectrum trading. In simulation tests, the performances of optimal channel numbers allocated to cognitive IoT users are given to clarify this. For the parameter of effective communication benefit k, it depends on the SNR threshold and channel condition.

III. OPTIMAL SPECTRUM ALLOCATION

Based on the actual benefits of cognitive IoT user, its utility function can be expressed as

$$U_i = E_i - P_i = \varepsilon_i B \log_2(1 + 1.5/(\ln(0.2/BER_i^{tar}))\gamma_i) - X - Y\sum_{i=1}^{N} B_i \quad (5)$$

where $B = B_1 + B_2 + \cdots + B_v$ means the total spectrum band purchased by cognitive IoT users. And, the SINR at the receiver can be given as

$$\gamma_i = \frac{g_{ii}p_i}{\sum_{j=1, j\neq i}^{v} g_{ij}p_j + n_0} \quad (6)$$

where n_0 is the background noise. g_{ii} and g_{ij} are path loss between IoT transmitter and receiver.

Thus, (5) can be rewritten to be

$$U_i = \varepsilon_i \sum_{i=1}^{N} B_i \times \log_2(1 + \frac{1.5/(\ln(0.2/BER_m^{tar}))g_{ii}p_i}{\sum_{j=1,j\neq i}^{v} g_{ij}p_j + n_0}) - X - Y\sum_{i=1}^{N} B_i \quad (7)$$

Besides, the cognitive IoT terminals' actual benefits from the perspective of transmission capacity can also be analyzed. Suppose all the IoT users access the authorized channels by overlay mode in which cognitive terminal's transmission is only restricted by its own power rather than primary systems. For a cognitive IoT user j, according to Ref. [36], its transmission capacity on different sub-channels can be expressed by

$$C_j = \max_{P_j} \sum_{i=1}^{N} t_{ij} E_{g_{1i}} E_{g_{0i}} [Blog_2(1 + \frac{g_{1i}P_{ij}}{N_0 B})]$$
$$s.t.\ E_{g_{1i}} E_{g_{0i}} [P_{ij}] \leq P_{max} \quad (8)$$

where C_j is the capacity of user j, and t_{ij} is the time division of idle channel i. P_{max} denotes the maximal transmit power of cognitive IoT user. $E_x[g(x)] = \int_x g(x)f(x)dx$ is the expectation of random function $g(x)$ and $f(x)$ is the PDF of random variable x. g_{ij} denotes the path loss for cognitive user j to the receiver. N_0 denotes the power spectrum density, and B is the bandwidth.

Applying Lagrange method to solve the optimization problem, the following equation can be obtained

$$\begin{aligned} L(P_j, \zeta) &= \sum_{i=1}^{N} t_{ij} E_{g_{1i}} E_{g_{0i}} [B \log_2(1 + \frac{g_{1i}P_{ij}}{N_0 B})] \\ &\quad - \sum_{i=1}^{N} \zeta_i (E_{g_{1i}} E_{g_{0i}} [P_{ij}] - P_{0i}) \\ &= \sum_{i=1}^{N} E_{g_{1i}} E_{g_{0i}} [t_{ij} B \log_2(1+\frac{g_{1i}P_{ij}}{N_0 B}) - \zeta_i (P_{ij} - P_{0i})] \end{aligned} \quad (9)$$

where ζ is the Lagrange factor. Taking the derivative of this function, the optimal power allocation can be expressed as

$$P_{ij}^* = \begin{cases} \frac{t_{ij}B}{k_i^*} - \frac{N_0 B}{g_{1i}}, & \frac{g_{1i}}{k_i^*} \geq \frac{N_0}{t_{ij}}; \\ 0, & \text{others.} \end{cases} \quad (10)$$

Then, the maximal capacity that cognitive IoT device can receive is

$$C_j^* = \sum_{i=1}^{N} t_{ij} E_{\frac{g_{1i}}{\zeta_i^*} \geq \frac{N_0}{t_{ij}}} [B \log_2(\frac{t_{ij} g_{1i}}{\zeta_i^* N_0})] \quad (11)$$

Thus, the actual benefits of cognitive IoT terminals can be given as

$$\begin{aligned} U_j &= C_j^* - P_j \\ &= \sum_{i=1}^{N} t_{ij} E_{\frac{g_{1i}}{\zeta_i^*} \geq \frac{N_0}{t_{ij}}} [B \log_2(\frac{t_{ij} g_{1i}}{\zeta_i^* N_0})] - X - Y \sum_{j=1}^{N} B_j \end{aligned} \quad (12)$$

As the cognitive user's utility function given in (7) is a multi-objective optimization which cannot be fixed by usual methods such as convex optimization, pattern search optimization can be used to find the optimal spectrum allocation.

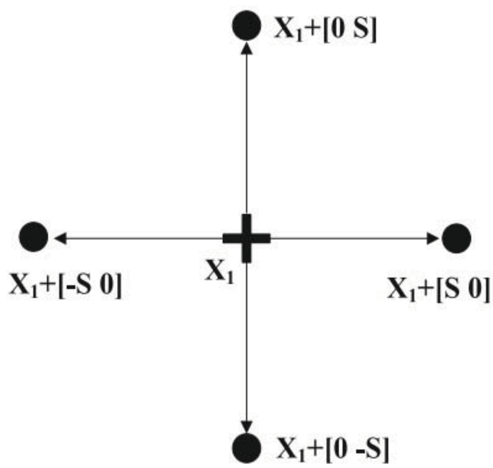

FIGURE 3. Pattern search optimization.

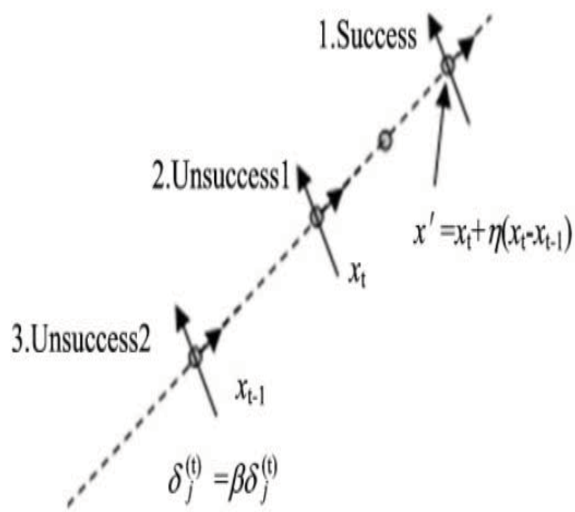

FIGURE 4. Schematic of pattern search method.

Pattern search optimization is a direct method to ascertain the optimal solutions which does not need the auxiliary information of objective function [37]–[39]. As shown in Fig. 3, the pattern search method will begin its searching from the initial point X and extend the searching from different directions. Besides, as shown in Fig. 4, the method will iterate from central point x_t and set an amplification factor $\eta > 1$ and constriction factor $\beta \in (0, 1)$. In the movement from point x_t to x_{t+1}, the searching will begin from referenced point y with regards to x_t. Then, the detectable searching continues with step length $\delta_1^{(t)}, \cdots, \delta_j^{(t)}$ for orthogonal vectors $d_1, \cdots, d_n$. If x_t iterates successfully, then next iteration begins from adjacent point $x' = x_t + \eta(x_t - x_{t-1})$. If the searching at x' succeeds, the method sets $x_{t+1} = x'$ and the new iteration departs from x_{t+1}. Otherwise, the searching unfolds from x_t. If it fails at point x_t, then it restarts from x_{t-1} and the step length reduces to $\delta_j^{(t)} = \beta\delta_j^{(t)}$. If the searching at x_{t-1} still fails, the method rollbacks to the process above.

In brief, the pattern search optimization method repeats the steps above-mentioned until one of the conditions below satisfy.

- Iteration number meets the maximal iteration value set.
- The mesh size reaches the minimal mesh tolerance.
- The fitness function changes very slightly which is less than given tolerance threshold.
- The distance between currently successful point and the next poll is less than given distance tolerance.
- The fitness function's evaluation times has reached the maximum.

It should be noted that the pattern search optimization has strong capability of searching, yet its search results are easily affected by initial point. Therefore, an optimal strategy is designed to select a proper initial point. Before identifying an optimal initial point, the optimization procedure should be performed for initial point selection. The pattern search algorithm will compare the results obtained by random initial points and the points returned by experiences, then ascertain the final initial point.

IV. NUMERICAL RESULTS

In this section, simulation tests are performed to testify the effects of our proposed method. A fixed area with 5km × 5km is considered where 15 cognitive IoT users and a base station locate as shown in Fig. 5. The interference from other cells or wireless networks is ignored. In this case, it is supposed that the cognitive IoT users located in this circumstance cannot use the authorized spectrum by other modes. This paper focuses on the dynamic spectrum access and optimal spectrum allocation in IoT. Essential modules including spectrum sensing, power management and spectrum switching are supposed to be equipped by the cognitive IoT devices.

Furthermore, it is considered the IoT is deployed in the environment of Rayleigh fading channels. The noise power is assumed to be $\sigma^2 = 2 \times 10^{-12}$mW. Besides, the expression of channel gain is subject to

$$g_{ij} = \frac{A}{r^\alpha} \tag{13}$$

where $\alpha = 4$ and $A = 10^{-10}$ which is corresponding to the path loss of 100dB for per km distance.

As shown in Fig. 6, the performance of fitness value with the increase of pattern search algorithm's generation is given.

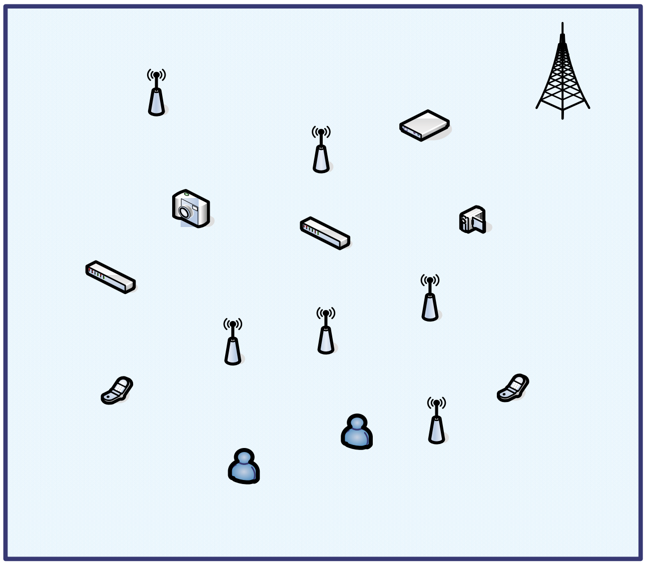

FIGURE 5. User distribution.

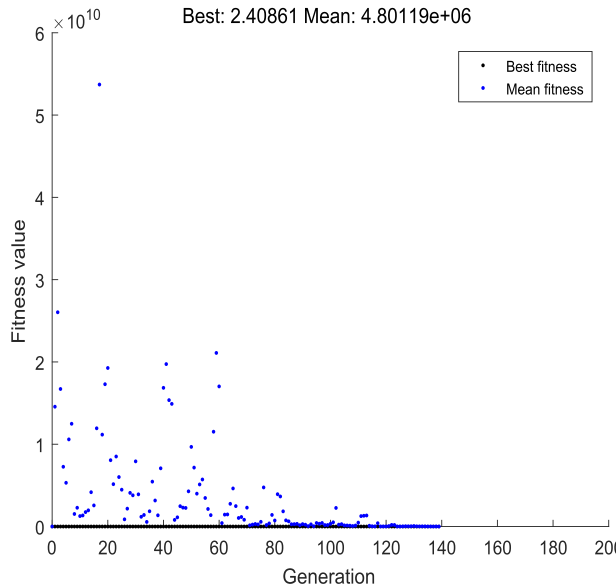

FIGURE 6. Fitness value of pattern search algorithm.

In this case, the fitness function is as following

$$F = \frac{1}{\omega U_i} \tag{14}$$

where U_i is obtained by (7) and $\omega = 10$. Furthermore, $\varepsilon_i \in [5, 10]$ and $X = 1$, $Y = 0.5$ are set. Then, for pattern search algorithm, $\beta = 0.6$ and $\eta = 1.2$ are considered. In addition, the user number is $N = 15$, the total bandwidth is $B = 2MHz$, and the channel number is 10, and proper channel reuse is utilized in our proposal. The fitness value is directly related to the objective function, and the minimal fitness value what the pattern search algorithm aims to find.

In this paper, we adopt equation (14) which depends on equation (7) as the fitness function for pattern search algorithm. As shown in equation (7), our ultimate objective is to find proper B_1, B_2, B_3, B_N for cognitive secondary users. Thus, there are many variables rather than one variable to be addressed. It is uneasy to use usual convex optimization method to fix the problem. Therefore, we adopt intelligent optimization algorithm to automatically search the optimal results.

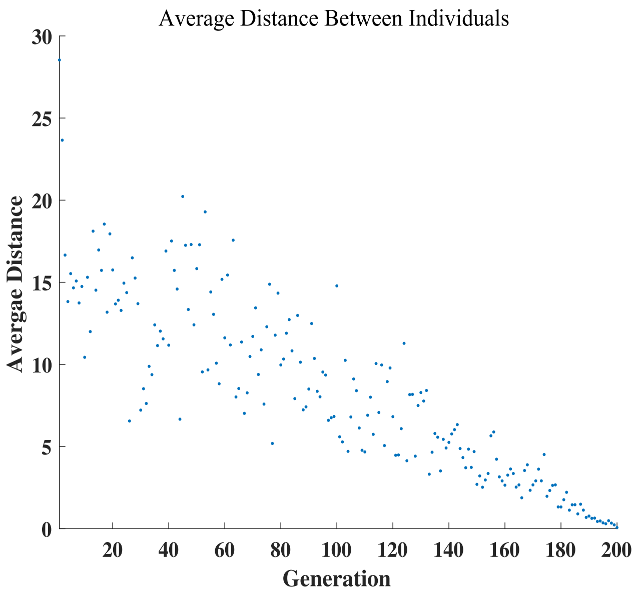

FIGURE 7. **Average distance of pattern search algorithm.**

Besides, in Fig. 7, the average distance of every generation has been given. Thus, with the decrease of average distance between individuals, the searching is approaching to the final destination. When the distance reaches the given threshold, the searching will stop. The average distance between fitness individuals means the difference between the fitness function between current generation and the previous generation.

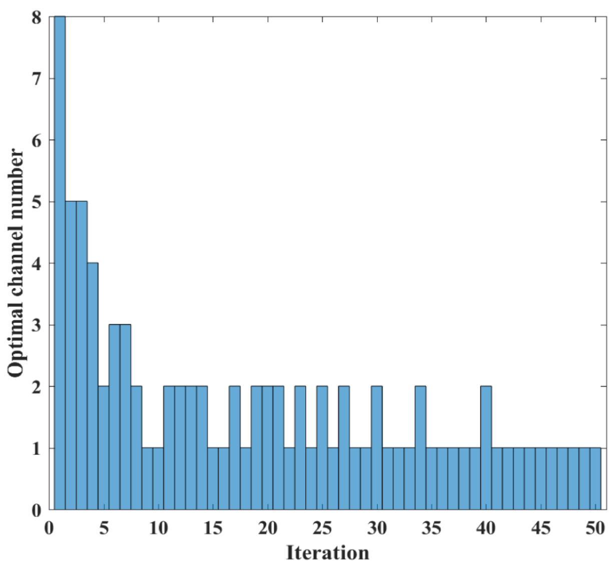

FIGURE 8. **Optimal channel number.**

Then, in Fig. 8, the number of selection number which means the channel number to be used is given. Randomly choose a cognitive IoT device as the target user and figure out the optimal channel number it should purchase. Thus, in this article, our solution designs a proper dynamic spectrum access strategy and give an optimal spectrum allocation method. The cognitive IoT user needs to maximize its utility function by balancing its actual benefits from this spectrum trading and its band demand. On the basis of satisfaction of essential band demand, it does not require to occupy more band for high-quality transmission.

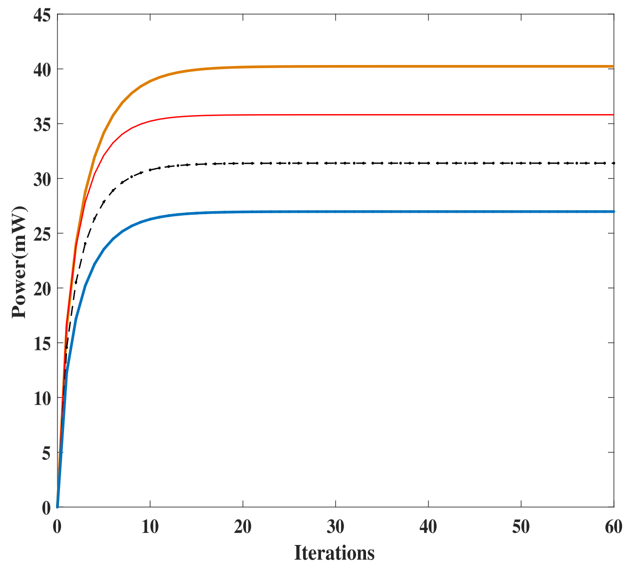

FIGURE 9. **Power allocation.**

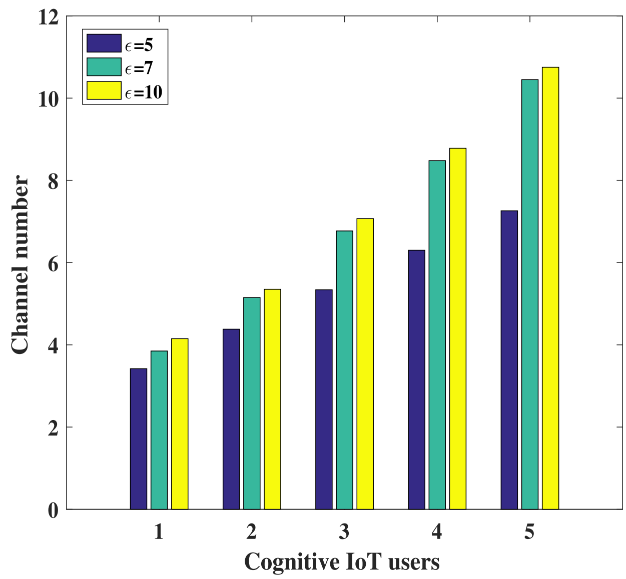

FIGURE 10. **Channel allocation.**

Besides, in Fig. 9 and Fig. 10, the performances of optimal power allocation and channel allocation in this cognitive IoT is given. As given in (10), the corresponding power allocation in case of optimal spectrum allocation is identified. Thus, cognitive IoT user's transmit power should also be optimized in dynamic spectrum access. Then, the optimal channel number of cognitive IoT users is also given in Fig. 10 where we choose random 5 secondary users' channel number for analyzing. With the increase of parameter ε implying more potential benefits for cognitive IoT users, it is envisioned that cognitive users' channel numbers can be increased to reap more revenues.

V. CONCLUSION

In this paper, the dynamic spectrum access and allocation in distributed cognitive IoT are investigated. The contribution of this paper mainly lies in that a trading-based dynamic spectrum management algorithm is introduced to improve cognitive users' spectrum access to authorized band. In our proposal, every single cognitive IoT device is considered to judge whether its actual benefits obtained from the spectrum dealing can exceed the cost it paid, then make a decision for accessing the spectrum in distributed mode. The cognitive IoT user's benefit is given in detail from the perspective of transmission capacity and BER in receiver. Based on the utility function of cognitive IoT user, it can make a proper option on this distributed dynamic spectrum access and the channel number for using. This dynamic spectrum access algorithm can be performed in distributed way where centralized control and base station are not essential. Besides, the performances of our proposal on spectrum and power allocation are provided in simulation section.

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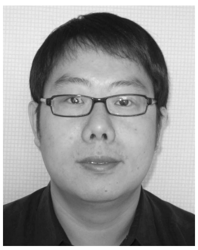

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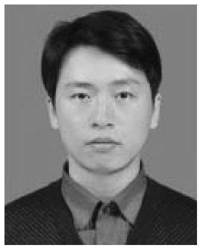

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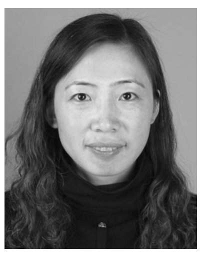

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